McGRAW-HILL PUBLICATIONS IN THE
AGRICULTURAL AND BOTANICAL SCIENCES
EDMUND W SINNOTT, Consulting Editor

ROOT DEVELOPMENT OF VEGETABLE CROPS

McGRAW-HILL PUBLICATIONS IN THE AGRICULTURAL AND BOTANICAL SCIENCES

EDMUND W SINNOTT, CONSULTING EDITOR

Adams—
FARM MANAGEMENT

Babcock and Clausen—
GENETICS IN RELATION TO AGRICULTURE

Babcock and Collins—
GENETICS LABORATORY MANUAL

Boyle—
MARKETING OF AGRICULTURAL PRODUCTS

Carrier—
BEGINNINGS OF AGRICULTURE IN AMERICA

Cruess—
COMMERCIAL FRUIT AND VEGETABLE PRODUCTS

Cruess and Christie—
LABORATORY MANUAL OF FRUIT AND VEGETABLE PRODUCTS

Eames and MacDaniels—
PLANT ANATOMY

Emerson—
SOIL CHARACTERISTICS

Gardner, Bradford and Hooker—
FRUIT PRODUCTION

Hayes and Garber—
BREEDING CROP PLANTS

Hutcheson and Wolfe—
FIELD CROPS

Loeb—
REGENERATION

Lohnis and Fred—
AGRICULTURAL BACTERIOLOGY

Piper and Morse—
THE SOYBEAN

Sharp—
CYTOLOGY

Sinnott—
BOTANY

Sinnott and Dunn—
PRINCIPLES OF GENETICS

Thatcher—
CHEMISTRY OF PLANT LIFE

Thompson—
VEGETABLE CROPS

Weaver—
ROOT DEVELOPMENT OF FIELD CROPS

Fawcett and Lee—
CITRUS DISEASES

Heald—
PLANT DISEASES

Rice—
THE BREEDING AND IMPROVEMENT OF FARM ANIMALS

Brown—
COTTON

Horlacher—
SHEEP PRODUCTION

Weaver and Bruner—
ROOT DEVELOPMENT OF VEGETABLE CROPS

McGRAW-HILL PUBLICATIONS IN THE ZOOLOGICAL SCIENCES

A FRANKLIN SHULL, CONSULTING EDITOR

Fernald—
APPLIED ENTOMOLOGY

Mitchell—
GENERAL PHYSIOLOGY

Shull, Larue and Ruthven—
ANIMAL BIOLOGY

Shull, Larue and Ruthven—
LABORATORY DIRECTIONS IN ANIMAL BIOLOGY

Snodgrass—
ANATOMY AND PHYSIOLOGY OF THE HONEYBEE

Van Cleave—
INVERTEBRATE ZOOLOGY

Wieman—
GENERAL ZOOLOGY

Shull—
HEREDITY

Pearse—
ANIMAL ECOLOGY

Rogers—
COMPARATIVE PHYSIOLOGY

These two series were originally published as one under the title of McGraw-Hill Agricultural and Biological Publications The late Dr C V. Piper was Consulting Editor from the inception of this series in 1917 until his death in 1926.

ROOT DEVELOPMENT

OF

VEGETABLE CROPS

BY

JOHN E WEAVER

Professor of Plant Ecology, University of Nebraska

AND

WILLIAM E BRUNER

Instructor in Botany, University of Nebraska

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC

NEW YORK 370 SEVENTH AVENUE

LONDON 6 & 8 BOUVERIE ST, E C 4

1927

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS COMPANY, YORK, PA.

TO

ROBERT JOHN WEAVER

PREFACE

This book is largely based upon investigations by the authors. The lack of exact knowledge and the frequently grossly inaccurate statements regarding the nature and extent of the root systems of vegetable crops have shown the need for intensive study. In dealing with the various vegetable crops the usually very meager data from other investigations have been added to present, so far as possible, a general view of root development of vegetable crops in the United States. No attempt has been made to include all of the root investigations in foreign countries but enough has been given to supplement adequately those in America and, it is believed, to include most of the important findings. The literature cited will direct the student who may wish to look further into foreign investigations.

The present work is a companion volume to Weaver's "Root Development of Field Crops." It is designed for the use of investigators and producers as well as to meet the needs of students of vegetable gardening.

In the study of root systems in relation to cultural practice, Thompson's "Vegetable Crops," Bailey's "The Principles of Vegetable Gardening," and similar works have been found very helpful. But in all cases original sources have been freely consulted in an attempt to correlate the root relationships with gardening practice.

All of the drawings with the accompanying root descriptions are original. Because of the great labor and expense involved in this work it could not have been accomplished except for the encouragement and financial support given by the Carnegie Institution of Washington. To this Institution the authors are under deep obligation for permission to publish this book as a companion volume to "Root Development of Field Crops." The authors are further indebted to Dr. Herbert C. Hanson for valuable assistance in the excavation of the roots at Lincoln. The senior writer is also indebted to a number of his students and especially to Mr. T. L. Steiger, Mrs. L. B. Mathews, and

Miss Annie Mogensen for most of the illustrations and other valuable help The authors wish to express their thanks to Professor T J Fitzpatrick for much helpful criticism in reading the manuscript and proof

THE AUTHORS

LINCOLN, NEBRASKA,
June, 1927

CONTENTS

CHAPTER VI

CHAPTER VII

CHAPTER VIII

CHAPTER IX

CHAPTER X

CHAPTER XI

CHAPTER XII

CHAPTER XX

CHAPTER XXI

CHAPTER XXII

CHAPTER XXIII

CHAPTER XXIV

CHAPTER XXV

CHAPTER XXVI

ROOT DEVELOPMENT OF VEGETABLE CROPS

CHAPTER I

INTRODUCTION

The plant is the most important agent in crop production. Soils, cultivation, fertilizers, irrigation, and other factors, in a sense, are all more or less subsidiary. Soils are modified by cultivation, by adding manure or other fertilizers, by drainage or irrigation, and in other ways with the express purpose of changing the environment so as to stimulate plants to increased productivity. Hence, it is not surprising that from time immemorial extended observations and, later, experiments have been made upon the aerial growth of crops under varying conditions. In fact an almost bewildering array of literature has resulted. But quite the converse is true of the underground parts. The root development of vegetable crops has received relatively little attention, and indeed accurate information is rarely to be found. The roots of plants are the least known, least understood, and least appreciated part of the plant. This is undoubtedly due to the fact that they are effectually hidden from sight. Notwithstanding the extreme difficulty and tediousness of laying the roots bare for study, it is not only remarkable but also extremely unfortunate that such investigations have been so long neglected.

It clearly seems that a thorough understanding of the activities of plants both aboveground and belowground and the ways in which these activities are favorably or unfavorably modified by various cultural practices should be basic for scientific crop production. Yet almost countless field experiments, selections, breeding, and testing of varieties, etc. have been carried on in all parts of the world with little or no knowledge as to the behavior of that very essential portion of the plant, the absorbing system. Similarly, in the study of soils, the greatest attention is given to the problems of the physics, chemistry, and bacteriology of this substratum and rather largely to the cultivated portion of the

surface only The soil, barring the living organisms which it supports, is perhaps the most complex, the most interesting, and the most wonderful thing in nature Surely it should receive thorough investigation But a study of the soil and the way in which its various relations affect yield without a consideration of the essential, intermediary absorbing system is more or less empirical A complete, scientific understanding of the soils-crops relations cannot be attained until the mechanism by which the soil and the plant are brought into favorable relationships, *i e* , the root system, is also understood

The student of plant production should have a vivid, mental picture of the plant as a whole It is just as much of a biological unit as is an animal The animal is visible as an entity and behaves as one If any part is injured, reactions and disturbance of the whole organism are expected But in the plant, our mental conception is blurred by the fact that one of the most important structures is underground Nor is the plant usually treated as an entity, it is often mutilated by pruning, cutting, and injuring the root system, frequently without much regard to the effect upon the remaining portion [61]

Modifying the Root Environment —In both field and garden the part of the plant environment that lies beneath the surface of the soil is more under the control of the plant grower than is the part which lies above He can do relatively little toward changing the composition, temperature, or humidity of the air, or the amount of light But much may be done by proper cultivation, fertilizing, irrigating, draining, etc to influence the structure, fertility, aeration, and temperature of the soil Thus, a thorough understanding of the roots of plants and the ways in which they are affected by the properties of the soil in which they grow is of the utmost practical importance Before other than an empirical answer can be given to the questions as to what are the best methods of preparing the land for any crop, the type of cultivation to be employed, the best time or method of applying fertilizers, the application and amount of water of irrigation, kind of crop rotations, and many other questions, something must be known of the character and activities of the roots that absorb water and nutrients for the plant and the position that they occupy in the soil

Adaptation of Roots to Environment.—By more or less profound modifications of their root system, many plants become

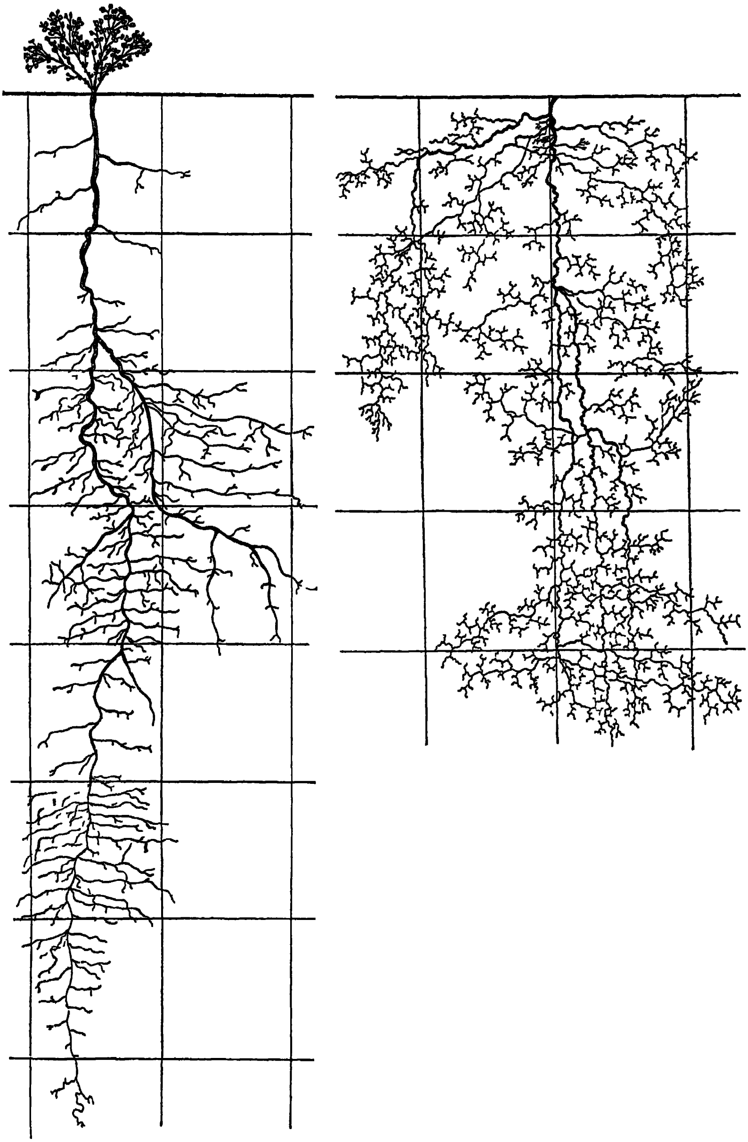


FIG 1—A spurge (*Euphorbia montana*) showing differences in root habit resulting from environment The plant on the left was excavated in the Great Plains of Colorado Maximum branching occurred in the third and fourth foot, although the taproot reached a depth of more than 7 feet The plant on the right, with a shallower but much more finely branched root system, was excavated from a "half-gravel slide" in the Rocky Mountains of Colorado

adapted to different soil environments, others are much less susceptible to change. Among forest trees, for example, the initial or juvenile root system of each species follows a fixed course of development and maintains a characteristic form for a rather definite period of time following germination. The tendency to change when subjected to different external conditions becomes more pronounced as the seedlings become older. But some species thus subjected exhibit much earlier tendencies to change than others and a widely different degree of flexibility is also shown. Hence, certain species, e.g., red maple (*Acer rubrum*), because of the great plasticity of their root systems, are able to survive, at least for a time, in various situations from swamps to dry uplands. The roots of others such as bald cypress (*Taxodium distichum*) are so inflexible that they can grow only under certain favorable conditions and their distribution is thus greatly limited.[160,161,48] Great variability also occurs in the rooting habits of fruit trees.[40,131,142]

Native herbaceous species usually show great plasticity of root habit, successfully adapting themselves to considerable differences in soil environment (Fig. 1). A few seem to be quite fixed in their habit of root growth.[167,168]

Continued study has shown that many field crops, although governed first of all by the hereditary growth characters of the species or variety, are usually subject to change. Certain varieties are able to adapt their root systems to unfavorable conditions much more readily than others.[174,86,87]

The wide range in soil and agricultural conditions under which vegetable crops are grown renders them particularly suitable both for the investigations of their root habits and also for a study of the agricultural significance of the differences encountered.

Root Adaptation and Crop Production.—Enough work has been done to show clearly that among garden crops root adaptations frequently occur. These will be pointed out in the following chapters, although a mere beginning has been made. The field is enormously large and difficult but one rich in possibilities. It seems entirely probable that some of the best-yielding crops are able to outstrip others largely because of their greater efficiency in securing a greater and more constant supply of water and nutrients. On the other hand, the failure of a crop to thrive in a particular soil may be due to a lack of adaptation of its root

system to the environment imposed upon it. Both of these conditions are illustrated by the growth of flax in India.

> The agriculture in many of these areas is ancient, there have been few innovations, and the soil conditions have had time to impress themselves on the varieties of crops cultivated. A condition of equilibrium between the type of plant and the soil has been obtained, as there has been ample time for the operation of natural selection. When we compare the root system of linseed from the black-soil areas with that of the varieties grown on the Gangetic alluvium, striking differences appear. The roots produced on the black soils (of the Peninsula) are deep, somewhat sparse, and are well adapted to ripen the plant quickly with the minimum of moisture. The type of gearing fits the soil. On the alluvium, where moisture is more abundant and where the aeration of the subsoil is poor, the root system is superficial but at the same time well developed. On the intermediate types of soil linseed produces a type of root about halfway between that of the black soils and of the alluvium. Once more the root system is found to fit the soil type. Further when we grow side by side on the alluvium these three classes of linseed, there is little or no adaptation of the roots to the new conditions, but the three types behave very much as they would in their native habitat. The deep, sparse root system of the black soil areas is developed in the alluvium, although it is fatal to the well-being of the crop. When the experiment is reversed and the types which suit the alluvium are grown on the black soils, there is again little or no adaptation to fit the new conditions. The linseed crop consists of a large number of varieties which differ from one another in all sorts of characters, including the extent and distribution of the roots. The root systems of the varieties are just as characteristic and just as fixed as the differences in the seed and other aboveground characters of these plants. A similar state of affairs obtains in other crops like wheat and the opium poppy, and is probably universal all over India.

Thus the differences between the root systems of varieties have been clearly shown and the economic significance illustrated.

Vegetable growing is an important phase of agriculture and one that is increasing at a rapid rate. In the United States practically every kind of soil is used for growing vegetables. Among the dozens or sometimes hundreds of varieties of the various vegetable crops, some undoubtedly have root systems more suited to a given soil environment than others. If the highest possible production is desired, attention should be given to selecting the variety that is not only climatically adapted but

also best fitted to a particular soil, modified as favorably as lies within the power of the grower It seems certain that a large part of the success in connection with the improvement of varieties consists in better adapting the absorbing system to the soil As stated by one who has extensively worked on plant selection, breeding, root investigations, and other phases of agronomic science, "The more I learn about cultivated plants the more I am convinced that the future lies in the root-soils relation and in matters which influence it "[60]

An intimate knowledge of the habits of growth of the root systems of vegetable crops will enable the grower to space plants to better advantage It should also permit him to intercrop or grow in succession such crops or mixtures that the soil volume will have a better distribution of roots and thus permit of methods of more intensive cultivation Similarly, by means of proper crop rotations and occasionally cultivating very deeply rooting crops, the subsoil may be kept in good condition and the effects of drought mitigated [126]

Interrelations of Plant, Soil, and Climate —In considering the importance of root relations in crop production, it should be clearly kept in mind that the plant, the soil, and the climate form a closely interlocking system of which no part should be overlooked or overemphasized It is now rather generally recognized that climate and vegetation are the most important factors determining the character of the mature soil [118] "The features assumed by the soil in its development from infancy, through youth, maturity, and old age, vary with the environment, especially with the climate and the vegetation "[102] The effect of both climate and soil on the growth of aboveground plant parts has long been known It has only recently been clearly demonstrated that the environmental factors which affect the root are not only those of the soil immediately about it but also those affecting the shoot which is rightly a part of the complex Through the shoot the root system is influenced by the aerial environment [23,103] The amount of light or the degree of humidity, temperature, etc and the effect of these upon food manufacture, water loss, and other activities affect root development In fact there is a rather close correlation between shoot and root development Whatever affects the aboveground growth of plants whether favorably or unfavorably is, in turn, very likely to exert an influence upon root development [171]

The complex relationship of plant, soil, and climate may be further illustrated in the use of fertilizers They modify the habit of growth as well as the composition of the plant For example, phosphates, when applied to soil upon which wheat or certain root crops are grown, promote deeper root penetration This results in a greater water and nutrient supply for the plant Earlier development and ripening may be promoted or drought mitigated Soils thus fertilized will produce crops under an environment perhaps otherwise quite unfavorable Vegetable production should be studied from the point of view of how roots and shoots of plants grow, and use should be made of the plant itself for indicating the direction of future research

An adequate discussion of the environment of roots (the soil), how roots are built to perform their work, and root habits in relation to crop production has been so recently given in "Root Development of Field Crops" that further statement seems unnecessary For a general discussion of the effects of irrigation, drainage, water content, aeration, temperature, nutrients, tillage practice, plant disease, and related phenomena upon root habit and their significance in crop production, the reader is referred to the same volume

Activities of Roots in Subsoil—The great extent of the root systems of most vegetable crops and their usual thorough occupancy of the subsoil may at once arouse interest concerning the importance of the deeper soil layers Experiments have shown that the roots of crops are active in the absorption of both water and nutrients even to the maximum depth of penetration [174, 165] Nutrients, when available, are taken from the deeper soils in considerable quantities, although to a lesser extent than from the soil nearer the surface which the roots occupy first and, consequently, at least in annual crops, where they absorb for the longest time The deeper portions of the root system are often particularly active as the crop approaches maturity Nutrients absorbed by them may produce a pronounced effect both upon the quantity and the quality of the crop yield [30]

Method of Root Study—In the present studies the direct method of root examination has been employed It has been used by the writer and his coworkers in the excavation of hundreds of root systems during the past 14 years and has proved very satisfactory By the side of the plants to be examined, a long trench is dug to a depth of about 5 feet and of convenient width

This affords an open face into which one may dig with hand pick and ice pick and thus uncover and make a careful examination of the entire root system This apparently simple process, however, requires much practice, not a little patience, and wide experience with soil structure In every case several plants were examined at each stage of development to insure an adequate idea of the general root habit As the work of excavation progressed, the trench was deepened, if necessary, so that finally

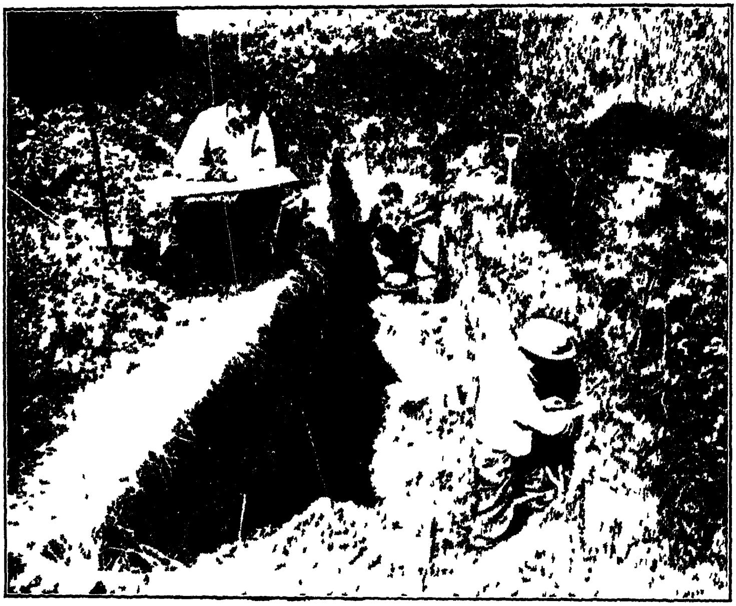


FIG 2—Trench used in the study of root systems In this case 3-year-old trees were being excavated They did not extend deeper (5 to 8 feet), however, than many vegetable crops of a single season's growth

the soil underlying the deepest roots was removed Frequently, the trenches reached depths of 6 to 11 feet (Fig 2)

Upon excavating the roots, detailed notes and careful measurements were made in the field After several plants were examined, these notes were studied and any point that remained indefinite was at once clarified by further study This method leads to a high degree of accuracy Drawings of the root systems were made in the field on a large drawing sheet with pencil and later retraced with India ink. They were made simultaneously

with the excavation of the roots and always by exact measurements In the drawings the roots are arranged as nearly as possible in a vertical plane, that is, each root is placed in its natural position with reference to the surface of the soil and a vertical line from the base of the plant In some cases the drawings represent the roots in their natural position in the surface foot of soil In every case it was sought to illustrate the average condition of root development rather than the extreme Although the drawings were made on a large scale, the rootlets were often so abundant that it was quite impossible to show the total number Such drawings, however, carefully executed, represent the extent, position, and minute branching of the root system even more accurately than a photograph, for under the most favorable conditions, especially with extensive root systems, the photograph is always made at the expense of detail, many of the finer branches and root ends being obscured

CONDITIONS FOR GROWTH AT LINCOLN, NEB

Since roots, like aboveground parts of plants, are greatly modified by environment, a brief statement will be given of the conditions under which the crops were grown

Soils —The vegetable crops at Lincoln were grown in a fertile, dark-brown, Carrington silt loam Preceding them white clover had been raised for 2 years This was followed by a crop of maize The soil was not only in an excellent condition as regards tilth but also was well supplied with humus In general, it may be said that the soils of eastern Nebraska have a sufficient supply of all the essential nutrients to insure good crop yields, except that, owing to the systems of cropping, there may be a deficiency in available nitrates The area was only slightly rolling, the general slope being toward the south As usual, some differences in soil texture were found in excavating the root systems in different parts of the area The following description of the soil profile represents an average condition

The surface 12 to 14 inches was a mellow, very dark silt loam from which the roots were readily removed At greater depths it intergraded into a dark-colored, clay subsoil This became quite sticky when wet and hard when dry It exhibited a columnar or jointed structure, especially below 18 inches, cracking badly when it shrank upon drying Roots were removed with much more difficulty from this soil layer At about 3 feet in

depth the subsoil became much lighter yellow in color and graded rather abruptly into an easily worked, quite mellow, friable soil type approaching loess in many of its physical properties This extended beyond the depth of greatest root penetration, *i e*, over 12 feet It was characterized by rusty streaks and numerous small calcareous areas and concretions Earthworm burrows penetrated the soil to depths of 8 feet or more and numerous old-root channels extended almost as deeply In many places extensive surface cracks reached depths of 4 to 5 feet They were sometimes 1 inch in width These crevices had been formed during past years of drought and were filled with rich, black, surface soil which had been washed or blown into them Cultural operations in a large measure had also undoubtedly contributed to the filling

Mechanical analyses of the soil at the several depths to 5 feet, together with the hygroscopic coefficients are given in Table 1

TABLE 1—MECHANICAL ANALYSES AND HYGROSCOPIC COEFFICIENTS OF SOIL FROM LINCOLN, NEB

Depth of sample, feet	Fine gravel, per cent	Coarse sand, per cent	Medium sand, per cent	Fine sand, per cent	Very fine sand, per cent	Silt, per cent	Clay, per cent	Hygroscopic coefficient
0 0–0 5	0 00	0 21	0 20	0 73	29 51	34 44	34 86	11 6
0 5–1 0	0 00	0 15	0 17	0 55	32 21	29 24	37 66	13 8
1–2	0 00	0 05	0 07	0 26	22 15	30 66	46 80	16 1
2–3	0 00	0 02	0 04	0 16	19 56	31 01	49 20	17 1
3–4	0 00	0 00	0 02	0 09	22 18	33 57	44 18	14 7
4–5	0 22	0 10	0 06	0 17	24 73	37 35	37 36	14 2

The fine texture of the soil is reflected in the rather high hygroscopic coefficients at the several depths This, of course, denotes also a high water-holding capacity

Number and Size of Plats—The crops, in nearly all cases, were grown in triplicate plats so that early, midsummer, and later examinations could be made without disturbing the areas in which the plants were to make further growth The plats, although somewhat variable in size, were in all cases large enough to permit of normal field development, each group of plants being entirely surrounded by plants of its kind For example, the plats of lettuce, radishes, and onions were 12 feet long and 10

feet wide, the plants in the central portion of each plat being used for a single root study In the case of the tomato, cabbage, eggplant, and other crops where each plant occupied considerable space, the plats were proportionately larger so that the plants examined were grown under the ordinary competitive conditions and mutual environment of garden crops

Tillage —The field was plowed 8 inches deep early in the spring after all cornstalks, stubble, and dried weeds had been carefully removed This was followed by repeated harrowing until an excellent, firmly compacted, moist seed bed of good soil structure was formed On areas not immediately planted, weeds were removed by raking and hoeing After the seeds were sown or the seedlings transplanted, further cultivation was done very shallowly with rake or hoe so as not to disturb the roots Cultivation and weeding were repeated, as in ordinary gardening, when needed to prevent the growth of weeds and to keep the surface soil in a good condition of tilth At no time did cultivation extend to greater depths than 1 inch

Precipitation —The rainfall of 19 2 inches during the 6 months of the growing season was 2 3 inches below the normal, with periods of moderate drought occurring in May and again in July

April with a deficiency of 1 2 inches had three well-distributed showers In May efficient rains occurred on the eighth and fifteenth, with a monthly deficiency of 3 inches June was a wet month with a total of 6 6 inches of precipitation, mostly in seven well-distributed rains This was 2 3 inches above the mean July had four rains during the latter half of the month and a total precipitation 1 8 inches below the mean Five well-distributed showers fell in August, an excess of 1 2 over the mean September had only 0 2 inch above normal, the rains also being well distributed

As a whole the growing season was typical for eastern Nebraska The spring was cool, frost occurring until about May 12

Soil Moisture.—It is a well-established fact that rainfall is only a very general indicator of soil moisture, since many other factors both climatic and edaphic intervene between precipitation and water available for plant growth Hence, a study of the soil moisture in several of the plats was made from time to time throughout the growing season Ideally this should have included determinations for each kind of crop at frequent intervals Owing to the laborious task of excavating roots this was not attempted.

TABLE 2—APPROXIMATE AVAILABLE SOIL MOISTURE, i e, AMOUNT ABOVE THE HYGROSCOPIC COEFFICIENT, IN THE SEVERAL PLATS DURING THE GROWTH OF THE CROPS, 1925

Depth, feet	Cabbage				Beets			
	May 29	June 10	June 24	Aug 4	May 29	June 10	June 30	Aug 13
0 0–0 5	7 6	5 4	13 1	12 5	13 0	8 8	14 9	17 5
0 5–1 0	9 0	8 0	12 5	3 4	12 5	10 2	12 6	12 8
1–2	12 3	8 9	10 4	4 0	10 0	8 0	10 4	1 6
2–3	7 5	7 2	9 3	2 9	5 6	3 8	9 7	1 0
3–4		9 6	7 7	4 0		3 9	10 0	2 1
4–5			9 0				11 6	2 6
5–6								6 7
6–7								9 0

Depth, feet	June 17	July 13		July 25	Aug 22		Aug 29	Oct 5	
	Peas	Lettuce	Radish	Sweet corn	Sweet corn	Cucumber	Rutabaga	Rutabaga	Parsnip
0 0–0 5	18 8	2 4	3 8	0 3	12 4	18 1	1 6	5 2	12 3
0 5–1 0	13 5	5 4	7 5	0 4	10 7	14 8	0 3	4 0	9 7
1–2	7 1	6 9	8 3	2 1	4 7	12 4	0 7	4 5	8 0
2–3	4 2	8 4	8 3	2 4	2 4	9 3	2 7	2 4	6 9
3–4	4 2	9 1	7 9	3 4	3 4	7 1	2 5	2 2	5 0
4–5		10 5	11 7	4 3	3 8			11 4	
5–6								17 4	

An examination of Table 2 shows that in both the cabbage and beet plats sufficient water was available until the middle of August to promote a good growth On July 25 sweet corn, which uses water in large amounts, had rather thoroughly depleted its supply of soil moisture, especially in the surface soil, but later in the season sufficient water was again present to promote normal development Differences in the degree of soil-moisture depletion by the various crops will be discussed when the root habits of the crops are considered

Temperature—The temperature of the air is an important factor not only directly in promoting metabolic processes but especially in connection with root studies in modifying humidity

and affecting transpiration. The amount of water lost from the aboveground parts reflects itself in the development and extent of the absorbing organs.

Table 3 gives the average day temperatures (6 a.m. to 6 p.m., inclusive) for the several weeks. These data were obtained in the usual manner from the records of a thermograph placed in an appropriate shelter in the field. It records the shade temperature at a height of 5 inches from the soil surface. The average daily (24-hour) temperatures are also included. Except for a few extremely hot days, temperatures throughout were very favorable for growth.

TABLE 3.—AIR TEMPERATURES IN DEGREES FAHRENHEIT DURING 1925

Week ending	May 13	May 20	May 27	June 3	June 10	June 17	June 24	July 1
Average day	57.3	61.9	67.9	78.0	80.0	81.5	82.8	77.3
Average daily	49.5	57.5	60.0	74.6	74.3	77.9	78.7	72.1

Week ending	July 8	July 15	July 22	July 29	Aug. 5	Aug. 12	Aug. 19	Aug. 25
Average day	88.4	90.1	82.0	78.2	74.0	77.4	81.2	79.4
Average daily	82.5	84.5	76.0	74.1	64.8	73.2	76.8	74.8

A continuous record of soil temperatures at a depth of 6 inches was obtained from May 16 to Aug. 25. During May the temperature ranged between 58 and 82°F., except on May 17 when a temperature of 50°F. was reached. The daily variation never exceeded 15°F. and was usually about 10°F. In June a variation from 62 to 90°F. was found, although the daily range did not usually exceed 12°F. But on one day a range of 19°F. was recorded. The soil at this depth was warmest at 6 p.m. and coldest at 8 a.m. This condition held throughout the summer. It represented a lag of nearly 4 hours behind the maximum and minimum air temperatures, respectively. Throughout July the temperature varied between 65 and 94°F. The daily range was usually through 15°F. (maximum, 18°F.), the highest and lowest temperatures occurring as in June. In August a temperature range from 61 to 89°F. was found, the daily range being slightly greater than for July.

The soil above 6 inches was not only much warmer at times but also subject to greater temperature fluctuations than at

greater depths Thus roots lying close to the surface of the soil were subject to the influence of an environment which was quite different from that affecting those growing more deeply It seems probable that surface-soil temperatures never became so high as to be injurious to root growth but that the absence of roots or their death in the shallowest soil was due to lack of a sufficient supply of moisture [15,174] Soil temperatures are also of great importance because of their relation to disease-producing organisms that may greatly limit successful crop production [170]

Humidity.—The loss of water through transpiration is directly controlled in a large measure by the amount of moisture already in the air This is also an important factor governing the evaporation of water directly from the surface soil Consequently, a record of relative humidity was obtained by means of a hygrograph appropriately sheltered with the recording apparatus about 5 inches above the soil surface Table 4 gives the average day humidity (6 a m to 6 p m , inclusive) and the average daily humidity (24 hours) for the several weeks from May 13 to Aug 25

TABLE 4—RELATIVE HUMIDITY IN PER CENT, 1925

Week ending	May 13	May 20	May 27	June 3	June 10	June 17	June 24
Average day	56 9	58 9	44 0	59 5	53 5	67 5	71 8
Average daily	65 0	67 0	55 2	65 2	62 0	75 8	81 6

Week ending	July 1	July 15	July 22	July 29	Aug 5	Aug 12	Aug 19	Aug 25
Average day	54 7	51 8	41 7	54 2	53 1	70 2	56 7	54 8
Average daily	66 4	61 6	55 6	63 1	63 8	78 6	67 3	63 1

The rather low relative humidities promoted high rates of transpiration, which in turn undoubtedly stimulated an active growth of roots

Evaporation.—Evaporation was measured by Livingston's standardized, non-absorbing, white, cylindrical atmometers These were placed in a bare area in the field with the evaporating surface at a height of 2 to 4 inches above the surface of the soil.

Table 5 gives the average daily evaporation by weeks from Apr 16 to Aug 29 These data clearly show that during the last half of May and periods in June and July the evaporation was quite high

TABLE 5—AVERAGE DAILY EVAPORATION IN CUBIC CENTIMETERS, 1925

May 16 to 30	May 30 to June 17	June 17 to 24	June 24 to July 11	July 11 to 22	July 22 to 29	July 29 to Aug 5	Aug 5 to 12	Aug 12 to 25	Aug 25 to 29
43 7	32 0	22 0	43 5	43 7	35 5	31 5	19 3	25 4	35 0

CONDITIONS FOR GROWTH AT NORMAN, OKLA

The greater portion of root studies in Oklahoma was made during 1926 Some work was also done the preceding growing season and the root growth of several crops was followed during the intervening winter Where root excavations were made in Oklahoma this is so stated in the text

Soil —The crops were grown in a fine sandy loam soil that had been heavily manured for a number of years and used for growing vegetables It was in excellent condition as regards tilth and amount of humus The area was level and the soil quite uniform throughout The surface foot had a reddish-brown color, was quite sandy in texture but rather compact, and contained enough clay to exhibit a tendency to bake when it dried after heavy rains In the second foot it was a light-chocolate brown and contained more clay When dry, it became quite hard, especially at a depth of 18 to 24 inches The greater sand and smaller clay content of the soil prevented it from cracking and fissuring as did the soil at Lincoln This, as will be shown, had a marked effect upon general root habit and branching Roots penetrated the 18- to 24-inch soil layer with some difficulty, especially when it was rather dry This was shown by their tortuous courses The third foot consisted of a reddish-yellow sandy clay It contained numerous, small, black concretions of iron 1 to 2 millimeters in diameter After long periods of drought it became very hard The next 18 inches were much sandier and had more and larger concretions but showed no change in color At greater depths the soil became still sandier, was mottled with reddish-brown spots, and contained many concretions At 7 to 8 feet it was very compact Table 6 shows the sizes and pro-

portions of the various soil particles at the several depths together with the hygroscopic coefficients

TABLE 6 —MECHANICAL ANALYSES AND HYGROSCOPIC COEFFICIENTS OF SOIL FROM NORMAN, OKLA

Depth of sample, feet	Fine gravel, per cent	Coarse sand, per cent	Medium sand, per cent	Fine sand, per cent	Very fine sand, per cent	Silt, per cent	Clay, per cent	Hygroscopic coefficient
0 0–0 5	0 00	0 66	2 28	14 01	47 14	19 84	16 07	5 2
0 5–1 0	0 00	0 65	1 70	7 54	47 14	22 50	20 16	6 7
1–2	0 00	0 55	1 97	8 66	41 56	19 59	27 67	8 5
2–3	0 00	0 41	1 35	6 55	29 45	27 96	31 26	9 7
3–4	0 00	0 61	2 42	12 05	33 78	20 96	30 16	9 2
4–5	0 00	1 07	3 66	16 33	36 67	12 96	29 30	8 9
5–6	0 00	1 08	3 94	18 31	36 30	13 39	26 97	8 5

Method of Planting and Tillage.—The field was plowed to a depth of 8 inches late in March Repeated disking and harrowing resulted in a good, compact seed bed All of the crops were planted by hand, each in four to eight rows, 3 5 feet apart in order to permit of cultivation with a horse-drawn harrow Shallow cultivation was given after each rain to prevent the formation of a surface crust and also to kill weed seedlings A mulching fork, supplemented by a hoe when necessary, was used near the plants In this manner a surface mulch 1 to 1 5 inches deep was maintained but in no case was a cultivation deeper A good supply of moisture was present just below the mulch during almost the entire growing season

Precipitation.—The rainfall of 11 5 inches during the period when the crops were grown (April to July, inclusive) was 3 6 inches below the mean

April with 1 9 inches had a deficiency of 1 3 inches and no efficient rainfall after the tenth May had 2 3 inches which was somewhat (3 1 inches) below the normal amount No efficient rain fell between May 8 and 30 During June precipitation was 1 6 inches less than the mean A precipitation of 2 2 inches, however, was fairly well distributed throughout the month July had 5 1 inches rainfall, 2 4 inches above the mean, little moisture falling after the thirteenth

Soil Moisture —Notwithstanding the rather limited rainfall, a good supply of water was present throughout the entire growing

season The fine sandy loam soil of the level field, loose from the cultivation of the previous season, had been thoroughly wet by the fall and winter rains Water had entered the deeper subsoil and moistened it beyond the depth of greatest root penetration Most of this water was retained in the spring and supplemented by rains in March Thus, although the summer rainfall was light, a good supply of moisture was present throughout the entire growing season

Since soil samples were taken from the middle of the area between the rows, the earlier determinations represent the total available moisture Later the widely spreading roots extended into these areas and the water supply was considerably reduced (Table 7)

TABLE 7 —AVERAGE APPROXIMATE AVAILABLE SOIL MOISTURE, *i e*, AMOUNT ABOVE THE HYGROSCOPIC COEFFICIENT, IN THE PEPPER AND SWISS CHARD PLATS AT NORMAN, OKLA, 1926

Date	0 0 to 0 5 foot	0 5 to 1 0 foot	1 to 2 feet	2 to 3 feet	3 to 4 feet
Mar 11	8 6	11 5	10 5	5 3	7 8
Mar 18	10 6	12 2	10 1	7 5	8 3
Mar 25	10 2	10 4	9 0	7 8	7 6
Apr 1	14 6	15 5	12 3	9 0	7 7
Apr 8	11 6	13 3	10 7	8 9	8 7
Apr 15	13 9	13 9	12 2	10 3	9 5
Apr 22	10 9	11 0	11 2	9 6	10 3
Apr 29	9 8	12 3	10 1	9 0	10 1
May 6	13 6	14 0	11 9	10 5	9 9
May 13	14 5	14 0	11 5	7 2	10 6
May 20	10 1	12 9	10 8	9 8	9 3
May 27	15 3	10 6	10 3	9 4	10 2
June 3	9 4	11 2	10 6	9 5	9 3
June 10	3 5	7 2	5 7	7 8	7 9
June 17	6 4	13 5	10 7	10 5	10 3
June 24	8 9	11 3	9 9	9 3	9 4
July 1	7 0	6 5	9 0	7 0	8 7
July 8	12 1	7 1	8 1	6 2	7 3
July 15	8 0	4 0	8 0	5 4	7 7
July 22	4 3	3 4	5 9	5 3	8 1

An examination of Table 7 shows that the soil was moist when the crops were planted and that sufficient water was available at all times to promote a good growth That conditions of soil

moisture in the plats of pepper and Swiss chard were representative for the crops as a whole was shown by frequent soil sampling among the roots of other vegetables. In nearly every case very similar results were obtained. This, however, was to be expected, since the root habits of both pepper and Swiss chard are representative and their aboveground transpiring parts moderately extensive. The excellent moisture content in the surface 6 inches was undoubtedly in part due to the soil mulch preserved at all times.

Other Factors.—Another factor favorable to moisture conservation was a very cool, late spring. Warm weather did not begin until the second week in April. The surface soil warmed rapidly, there was enough moisture to promote prompt germination and vigorous growth, and the crops made excellent progress even under a light precipitation. The usual drought and high temperatures of July were replaced by a relatively cool, moist midsummer during which the plants made a continuous growth. The average day temperatures (6 a.m. to 6 p.m., inclusive) and the average daily temperatures (24 hours), obtained by means of a thermograph placed in the field as at Lincoln, are shown in Table 8.

TABLE 8.—AIR TEMPERATURES IN DEGREES FAHRENHEIT, AND AVERAGE DAILY EVAPORATION IN CUBIC CENTIMETERS AT NORMAN, OKLA., 1926

Week ending	March		April					May	
	18	25	1	8	15	22	29	6	13
Average day temperature	53.3	60.3	40.6	52.4	50.0	61.4	72.6	77.7	72.2
Average daily temperature	48.8	55.0	38.5	47.4	46.9	56.9	65.0	69.9	67.6
Evaporation		26.6	10.2		7.0	21.7	39.1	29.1	21.8

Week ending	May		June				July			
	20	27	3	10	17	24	1	8	15	22
Average day temperature	84.8	90.0	83.8	86.4	85.4	80.6	86.8	94.6	86.5	86.2
Average daily temperature	76.8	87.9	78.8	79.3	79.7	75.3	79.1	89.8	82.1	81.8
Evaporation	39.1	46.4	26.1	41.7	48.0	17.3	29.0	51.4	22.7	31.0

The average daily evaporation from porous-cup atmometers, similar to those used at Lincoln, is also shown in Table 8. The

atmometers were placed in an uncropped area with the evaporating surface 6 to 9 inches above the ground An examination of these data shows that during two or three periods, occurring in May, June, and July, evaporation was very high This also indicates conditions for high transpiration The response was shown in deeply penetrating and widely spreading root systems to be described in the following chapters

Conditions for Growth during the Fall and Winter.—The root development of certain crops was studied during the preceding fall and winter Following a dry, late summer in 1925, September was warm and had an abundance of moisture (5 4 inches)

TABLE 9—CONDITIONS FOR GROWTH DURING FALL AND WINTER, 1925-1926, AT NORMAN, OKLA

Week ending	August			September				October	
	13	20	27	3	10	17	24	1	8
Average day temperature, degrees Fahrenheit	79 3	84 7	79 1	81 4	85 8	60 1	81 4	76 1	67 6
Average daily temperature, degrees Fahrenheit	75 6	79 7	76 0	75 8	78 7	53 1	77 5	71 8	63 4
Soil temperature, depth 6 inches, degrees Fahrenheit	82	84	84	86	84	65	79	72	71
Total precipitation, inches	0 90	0 00	0 00	0 00	1 00	5 25	1 49	1 16	1 79

Week ending	October			November				December		
	15	22	29	5	12	19	26	3	10	17
Average day temperature, degrees Fahrenheit	58 5	58 7	46 2	50 8	53 3	56 6	55 5	54 7	48 9	51 0
Average daily temperature, degrees Fahrenheit	56 1	55 6	41 1	46 5	47 9	45 3	46 5	49 1	43 3	44 6
Soil temperature, depth 6 inches, degrees Fahrenheit	67	62	60	61	60	62	60	57	50	47
Total precipitation, inches	0 45	0 24	0 00	0 08	2 01	0 04	0 03	0 00	0 29	0 00

Week ending	December		January				February			
	24	31	7	14	21	28	4	11	18	25
Average day temperature, degrees Fahrenheit	37 4	39 8	33 3	42 6	52 0	46 1	56 3	47 2	47 7	55 7
Average daily temperature, degrees Fahrenheit	32 4	33 3	29 9	38 1	47 0	41 0	48 7	40 6	41 4	47 9
Soil temperature, depth 6 inches, degrees Fahrenheit	44	38	34	36	43	43	54	48	49	52
Total precipitation, inches	0 00	0 00	0 00	0 00	0 00	0 00	0 00	0 00	0 07	0 09

During this period many long-lived vegetable crops showed a vigorous, renewed growth. Growth was continued, especially by the hardier plants, during an unusually cool October. Owing to favorable soil moisture and rather uniformly moderate temperatures during November and December, growth in several crops slowly continued. Following the cessation of growth in January, renewal of the development of both roots and tops was resumed during February which had a temperature of 8.2°F. above the mean.

The average day temperatures (8 a.m. to 6 p.m., inclusive) and average daily temperatures for the entire period, secured by a thermograph placed in the field, are shown in Table 9. Here also are included isolated readings of the soil temperature at a depth of 6 inches as well as the precipitation. The reader may wish to refer to these environmental conditions when studying the root development of the several crops, the description of which will now be taken up.

CHAPTER II

SWEET CORN

Sweet corn (*Zea mays rugosa**) is not only one of the most common but also one of the most important of vegetable crops Like field corn it may be grown on a wide variety of soils A corn plant requires more space than does the individual of any of its cereal relatives In many varieties the production of suckers or secondary stems or branches from the lower nodes is very pronounced These branches develop their own roots

Sweet corn of the Stowell's Evergreen variety, a standard, main-crop variety, was planted June 2 This is one of the old, well-known, and most important canning varieties It produces a rank growth The hills were spaced 42 inches apart and three to four plants were permitted to grow in each hill The grains were planted 2 5 to 3 inches deep Weeds were kept in check by repeated shallow cultivation

Early Development—An initial examination was made June 18, only 16 days after planting The plants were 7 inches tall, in the sixth-leaf stage, and had a leaf spread of 8 inches The total leaf surface averaged 45 square inches Unlike field corn, which usually has three roots making up the primary root system, sweet corn has but one This seed root was already 18 inches long on most of the plants examined Thus, allowing 3 or 4 days for germination, it had grown at the rate of over 1 inch a day The direction of growth was not downward but obliquely outward and downward The lateral spread was sometimes more than 1 foot, but none penetrated deeper than 11 inches (Fig 3) The last 3 inches of root were unbranched but the remainder was covered with branches at the rate of 25 per inch The younger ones were scarcely ¼ inch in length, but toward the seed they became progressively longer and many on the older portion of the root were 3 inches long A few were even more extensive, reaching a maximum length of 10 inches The longer and older

* The nomenclature is according to Bailey, L H, "Manual of Cultivated Plants," 1924

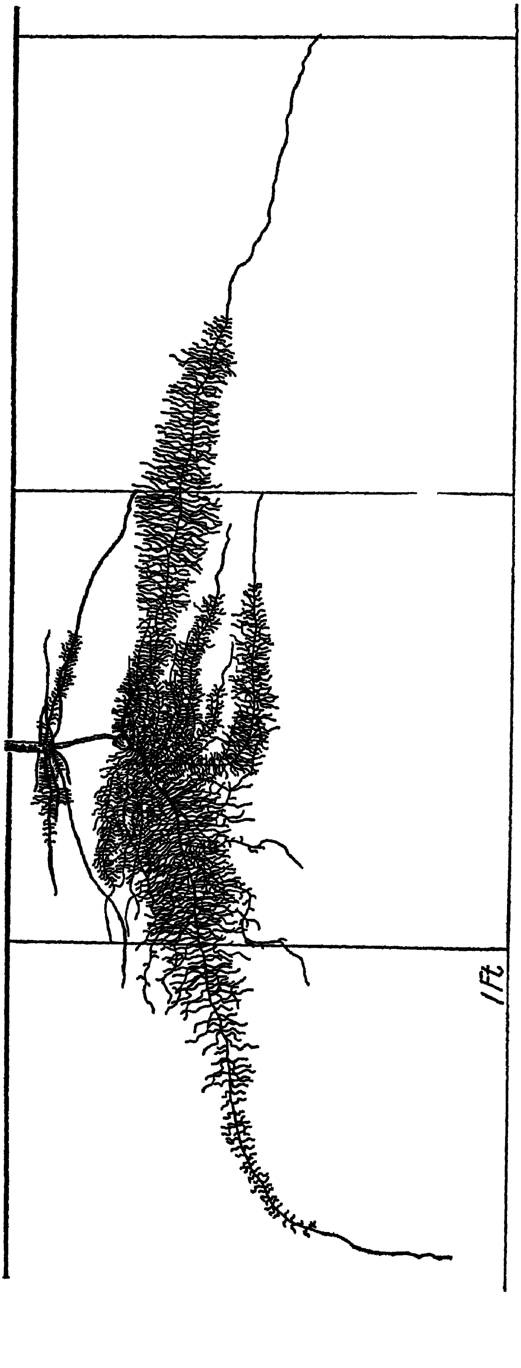


FIG 3 —Root system of sweet corn 16 days after planting The growth of the secondary root system is well under way

laterals were densely rebranched with laterals seldom exceeding ¼ inch, but the younger ones were simple Occasionally, a second long root arose from the base of the stem near the seed One of these is shown in the drawing

In this connection it is interesting to note that recent studies on field corn have shown a positive correlation between high seminal-root production and yield There is also some evidence that high seminal-root production tends to enhance vigor of early growth [141]

The secondary root system, originating from a node on the stem about 1 inch below the soil surface, had also begun to appear This consisted of 6 to 10 rather thick, mostly horizontally spreading roots Apparently these were of rather recent origin but were developing rapidly Some were 8 inches long, others just emerging from the stem The younger and shorter ones were smooth and unbranched like the 3 to 4 inches on the ends of the older ones Otherwise short branches occurred at the rate of 20 to 25 per inch Root hairs were very abundant and the roots were so covered with adhering soil particles, except the shiny white ends, that they appeared very thick and black even after removal from the soil Figure 3 shows that the total absorbing area of the roots really was quite large In the case of field corn it has been found to exceed that of the tops

Experiments with the smaller cereals, *viz*, wheat, barley, and rye, indicate that the primary root system (seminal roots and their branches) serve largely the main stem, whereas the nodal roots chiefly serve the tillers To what degree a similar relationship holds in sweet corn would constitute an interesting and valuable experiment [82]

Relation of Absorbing Area to Soil Moisture.[169]—In one experiment Nebraska White Prize dent corn of the F_1 generation from two pure-line parental strains and, consequently, of similar hereditary constitution was grown for 5 weeks in fertile loess soil with original water contents of 9 and 19 per cent, respectively, above the hygroscopic coefficient The plants were in the eighth-leaf stage when the roots were examined In the more moist soil the area of the tops, including the stem and both surfaces of the leaves, was 82 per cent of that of the roots But in the drier soil the tops had only 46 per cent as great an area as the roots In other words, the absorbing area of the roots (exclusive of root hairs which covered the entire root system) was 1 2 times as great

as the area of the tops in the more moist soil and 2.2 times as great in the drier soil. The total length of the main roots in the two cases was about the same, as was also their diameter. In neither case did the main roots make up more than 11 per cent of the total absorbing area. In the drier soil 75 per cent of the area was furnished by the primary laterals and the remaining 14 per cent by branches from these. But in the more moist soil the primary branches furnished only 38 per cent of the root area. It seemed as though the plant had blocked out a root system quite inadequate to meet the heavy demands for absorption made by the vigorous tops, and as the soil became drier the remaining 51 per cent of the area was furnished by an excellent development of secondary and tertiary branches.

Maize, in loess soil with only 2 to 3 per cent of water in excess of the hygroscopic coefficient, had, in proportion to the length of the main roots, about one-third more laterals than it had in a similar soil of medium water content. Moreover, the absorbing area in comparison to tops was greater.

Similar top-and-root area relations have been found to hold for other plants when grown in like soils of different water content. Numerous experiments have shown that root extent is greater in dry soil.[68] Because of the difficulty of recovering the root system in its entirety from the soil and the onerous task of measuring the length and diameter of all its parts, but few data are available. For example, a plant of maize only in the eighth-leaf stage has from 8,000 to 10,000 laterals arising from the 15 to 23 main roots. Usually the relations are stated in the ratio of the dry weight of roots to tops, an expression difficult of interpretation in terms of function. The larger, thicker, and heavier roots are least significant, the delicate branchlets, too often lost in such determinations, being of greatest importance although adding little to weight.

Midsummer Growth.—A second examination was made July 27. The plants had a height of about 4.5 feet and were very leafy. The parent stalk had usually given rise to two to four tillers but sometimes there were as many as six. The very numerous leaves, averaging 2.5 feet long and 3.5 inches wide at the base, offered a very large area for food manufacture and transpiration. For example, one plant with four tillers had a leaf surface of 20 square feet. The tassels were about half out.

The root system had made a really wonderful growth and was clearly in a state of very rapid development. After considerable

study a plant with four tillers was selected as typically representative, and was fully examined and described There were 45 roots of larger diameter, 3 to 4 millimeters These were older and longer than the others Another lot of 15 roots were about 1 5 millimeters in diameter and also extended widely In addition there were 33 young roots of a diameter of 1 5 to 3 5 millimeters and of an average length of 4 inches (varying from 1 2 to 8 5 inches) Finally, 29 smaller, fine roots only 0 5 millimeter thick and about 2 inches long arose from the root crown It is impossible to represent all of these in detail in the most carefully executed drawing But at least the principal features can be clearly portrayed (Fig 4)

The primary root (often erroneously called temporary), which could still be easily identified, pursued an obliquely downward and outward course, ending 28 inches horizontally from the base of the stalk and at a depth of 37 inches Only a few roots penetrated deeper One, however, was found near the 4-foot level, but the usual depth of maximum penetration scarcely exceeded 3 feet The working level was at a depth of 2 feet and a maximum lateral spread of 3 feet had been attained The working level, or the working depth, means that to which many roots penetrate and at which much absorption must occur

The thorough occupancy of even the surface 3 inches of soil and the competition of the roots between the 42-inch rows may be plainly seen The lax, meandering course of the longer main roots of the adventitious or secondary root system was such as to ramify the soil completely from the surface to directly beneath the plant These strong, tough roots were 3 to 4 millimeters in diameter at their origin and maintained a diameter of 1 5 to 2 millimeters to their tips They were extremely well branched Only the 3 to 5 inches of the rapidly growing root ends were free from branches The branches were usually most numerous and often longest throughout the first few feet of their course Here they were frequently distributed 18 to 25 per inch, but they were profuse throughout, *i e* , 8 to 12 per inch All of the branches are not shown in the drawing These were variable in length, the usual length of the shorter ones ranging from 0 2 to 2 inches But branches 6 inches to 2 to 3 feet long were also common The shorter rootlets were often unbranched, but longer ones (mostly those over 1 inch in length) were rebranched with 20 branches, 0 1 to 1 inch long, per inch These longer sublaterals were again

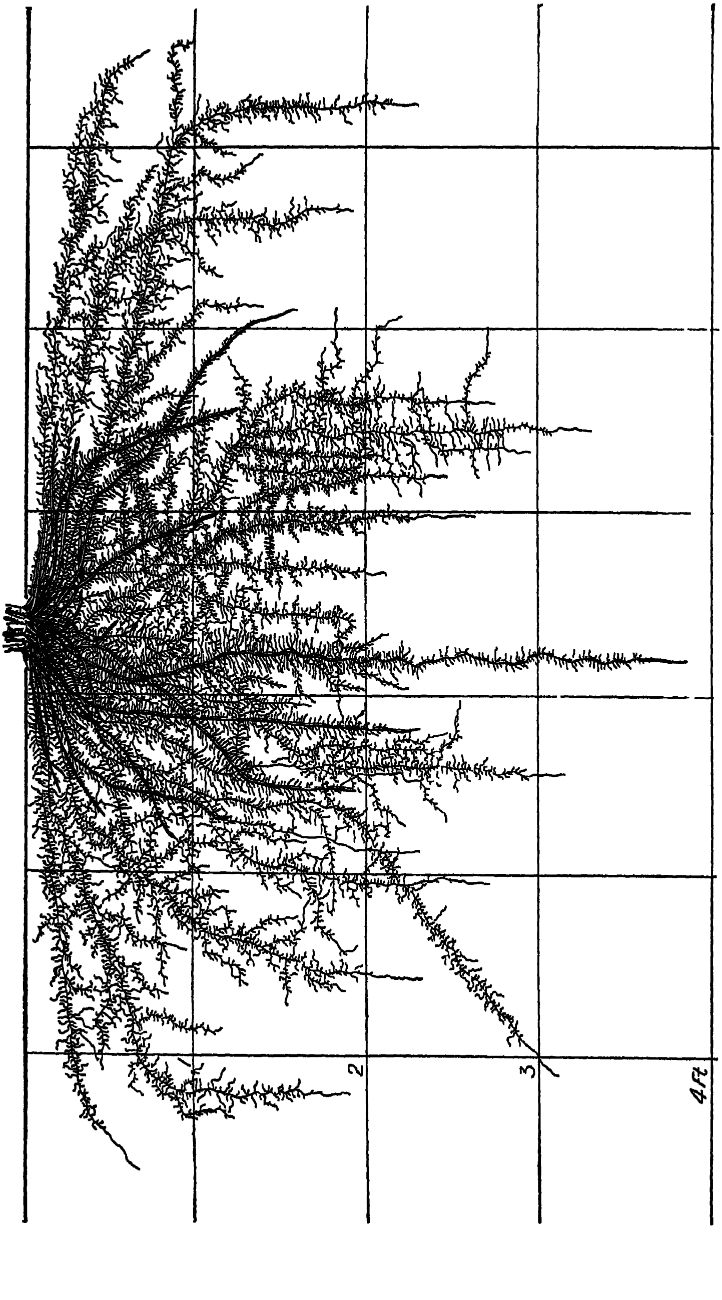


FIG 4 —Root system of sweet corn 8 weeks old

rebranched Often the larger branches on the main roots were 1 to 1 5 millimeters thick and branched like the main root Thus, dense masses of roots and rootlets ramified the soil

The root network was especially dense within a radius of 6 to 10 inches from the plant Here, in addition to the older roots, new surface roots were formed For example, one of these only 7 5 inches long was 5 millimeters thick It tapered to a tip 2 millimeters in diameter There was a total of 63 branches, many of which were profusely rebranched as shown in Fig 5, 33 roots

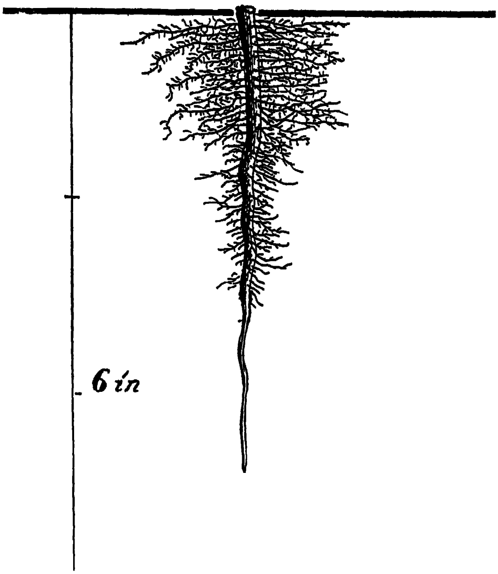


FIG 5 —One of the younger and shorter but densely branched roots of corn

of this general type were found near the base of the plant, and some actually had 40 branches per inch! Some aerial roots, as yet without branches, extended 2 to 4 inches into the root-filled soil All of the surface roots were very turgid and brittle In fact, the denseness and abundance of the rapidly growing roots can scarcely be overemphasized

Maturing Plants.—Late in August a final examination was made The plants had an average height of 5 3 feet, some stalks were 6 5 feet tall The leaves had not increased in average size but there were more of them owing to the development of the tillers, some of which were now as large as the parent plant.

Only a few of the basal leaves had deteriorated and the plants were in good condition The one selected for detailed study had five stalks and seven ears The kernels were well filled but the husks were only beginning to dry

The root system had developed proportionately to the tops Branchlets extended to the root tips and indicated that growth was practically complete The surface area delimited at the former examination (approximately 3 feet on all sides of the plant) had not been greatly extended, but the soil volume, of which this was one end, had been greatly extended in depth A working level of 50 inches was found and numerous roots ended between 60 and 68 inches, which was the maximum depth

After continued study a typical plant was selected and its root system worked out in the usual manner A total of 78 main roots (*i e*, roots of large diameter, 3 5 millimeters or more) arose from the base of this plant and 123 smaller ones Those of the latter group ranged from 0 5 to 2 millimeters thick Nine of the large main roots extended outward 18 to 42 inches from the base of the plant in the surface soil and then, turning downward, reached depths of 3 to 5 feet Twenty-five main roots (20 to 30 on other plants) extended outward only a short distance from the base of the plant or, more usually, ran obliquely downward in such a manner that even at their ends (at depths of 3 5 to 5 feet) they were only 12 to 18 inches from a vertical line from the base of the plant Figure 4 shows that some of these more vertically descending roots were half grown at the earlier examination But many more of them had developed at this time The remainder of the large roots consisted of prop roots and others with a large diameter (not infrequently 5 millimeters) which mostly extended only a short distance, usually not over 12 inches, from the base of the plant

As regards the remaining very numerous but smaller roots, these extended outward almost entirely in the surface foot of soil Here they ended at distances of 3 to 24 inches from the base of the plant Thus, the surface soil, especially the first 10 inches and within a radius of 9 inches from the crown, was filled with a dense tangle of roots, a network so complex and so profuse that there seemed actually to be more roots than soil Certainly no moisture could evaporate from this soil volume Indeed it seems many more roots were present than were necessary to exhaust it of its water and readily available nutrients! Figure 6 shows a

surface view of this root complex, the soil having been removed and the roots exposed to a depth of 12 inches.

As regards degree of branching, it was indeed profuse. On the main, long, widely spreading roots, laterals occurred as before at the rate of 8 to 12 branches per inch, but 30 branches per inch were not uncommon. Even at depths of 4 feet or more 5 to 10 short branches per inch were usual. The branches, moreover, were, in general, longer than at the earlier examination, in fact long branches (over 5 inches) were much more numerous, and the network of branches due to rebranching much more profuse. Similar branching occurred on the long, rather vertically descending main roots, but these, like the others, were less profusely branched below 3 feet. From the tough, yellowish, cord-like roots many long branches filled the soil. Some of these in the deeper soil were quite yellow in color. Branching of the finer surface laterals occurred at the rate indicated in the drawing. Here also the length of the branches and their degree of rebranching are shown in detail.

If one can visualize the root system of the sweet-corn plant, he will see the surface 12 inches of soil near the plant filled with a tangled root mass even to within 1 inch of the soil surface. Extending beyond this to distances of 18 to 42 inches, main horizontal roots pursue their course. From these long branches extend into the deeper soil and finally the main roots themselves turn downward and penetrate deeply. Below the 10-inch level, roots are still abundant, but not so dense, until the working level at 50 inches is reached. Still deeper roots are fewer but occasionally occur at a depth of 68 inches. The main vertical roots penetrating downward, spreading 12 inches or more on all sides of a vertical line from the base of the plant, so thoroughly fill the soil that in comparison there seems to be more or less of a gap between this soil volume and that so completely occupied by the main horizontal ones. In some plants this is less pronounced since, as in field corn, the roots spread at wider angles and thus thoroughly occupy this portion of the soil volume.

Summary.—Sweet corn is an important vegetable crop. The primary root system, unlike that of field corn, usually consists of a single, much-branched root. During the first few weeks this grows outward and downward over 1 inch a day. The secondary root system consists of numerous horizontally spreading roots which arise from the nodes of the stem just beneath the soil

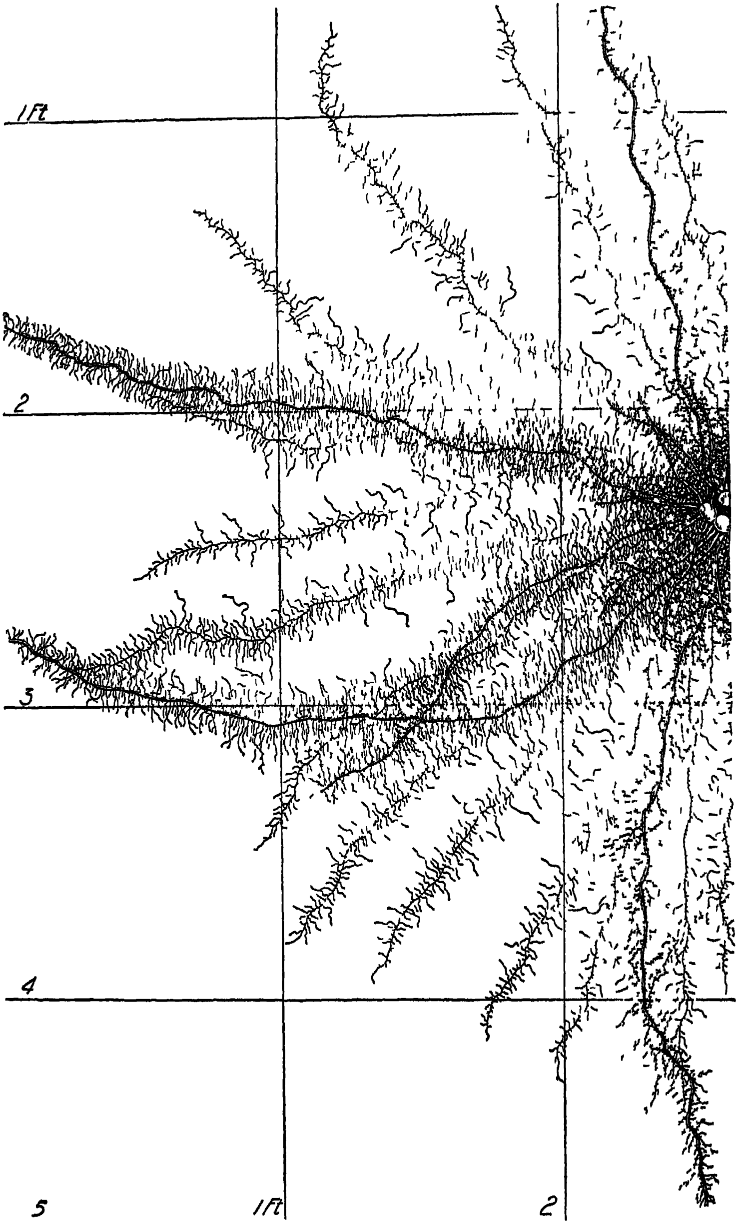
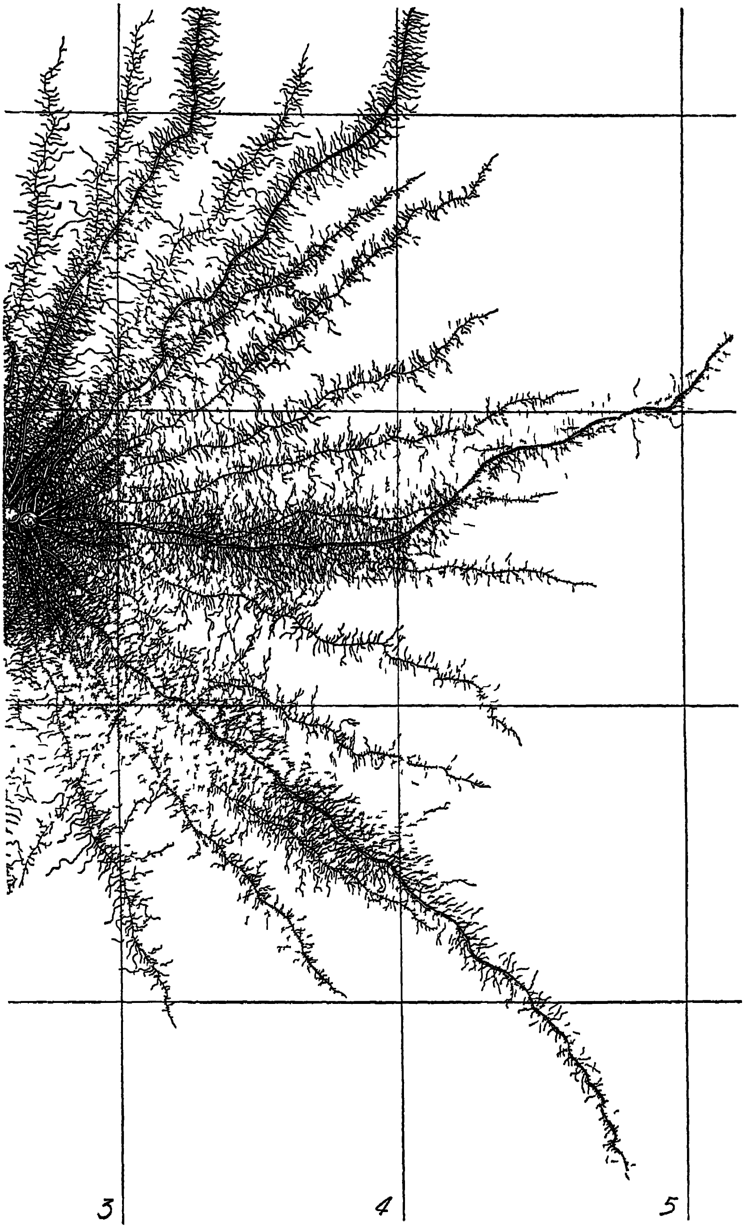


FIG 6—Roots of a mature plant of sweet corn found in the 12 inches of removed Where the larger roots appear to end, they really turned downward



suɪfaɪe soil They are shown ɪn their natural position after the soil had been ɪnto the deeper soil

surface. The roots are so profusely furnished with laterals that the absorbing area exceeds the area of the tops. In rather dry soil the absorbing surface is much greater than in soil that is more moist. Plants only in the eighth-leaf stage have from 7,000 to 10,000 branches. At the time of tillering both the primary and secondary root systems are still vigorously growing. The root system is composed of about 100 thick, coarse roots, about a third of which have just commenced growth, and approximately one-third as many finer ones. They spread 3 feet on all sides of the plant and thoroughly occupy the soil, interlacing between the rows, and reach a working depth of 2 feet. Maturing plants show 6 inches greater lateral spread and the soil is ramified to a depth of 5 feet. Thus, over 180 cubic feet of soil are occupied by the roots of a single plant. Branching is profuse, 8 to 30 long, much rebranched laterals occurring per inch of main root. Briefly, sweet-corn roots extend laterally more than half as far as the stalk extends upward, and the root depth is equal to the height of this rather imposing vegetable crop.

Comparison with Roots of Field Corn.—The root system of sweet corn is very similar to that of field corn. Field corn is usually of larger stature, has a greater lateral spread (often 3.5 feet on all sides of the plant), and penetrates more deeply, usually to 5 and sometimes to 8 feet. This deeply rooting habit has been observed in Nebraska,[174] Colorado,[68] Kansas,[105] Wisconsin,[80] Illinois,[58] and New York.[2] That it is greatly modified by irrigation,[68] drainage,[32] fertilizers, etc. has also been ascertained.[104,78,50] The root system of sweet corn is so similar to that of field corn and the plants are so closely related that it is believed that similar modifications of the soil environment would induce like responses in root development.

Further investigations will undoubtedly show that different varieties exhibit differences in rooting habit. Such information is of great scientific and practical value. For example, it has been shown that inbred strains of field corn differ greatly in the character and extent of their root systems. "Certain strains . . . have such a limited and inefficient root system that they are unable to function normally during the hot days of July and August, when the soil moisture is low."[58] Different strains show differences in resistance and susceptibility to root rot. It has further been shown that, in general, weak-rooted strains when compared with better-rooted ones, are more likely to lodge

and give a lower yield of grain [81] This is due in part to being more susceptible to injury from unfavorable environment and in part to parasitic factors [58] Experimental evidence has also been found which supports the suggestion that selective absorption by individual corn plants may prove to be a very important heritable character [56,57] The relation of the root habits to cultural practices in growing the crops of sweet and field corn are practically identical

Relation of Root Habits to Crop Production —A study of the root habit clearly shows why corn does best on a deep, well-drained soil which has an abundant and uniform supply of water throughout the growing season

Cultivation —If the soil is well prepared before planting, the main benefits of cultivation are derived from keeping down weeds, preventing the crusting of the surface, and keeping the soil receptive to rainfall The superficial position of the roots clearly shows why deep cultivation is harmful Fortunately, weeds are most easily destroyed when coming through the surface of the soil by shallow cultivation such as harrowing surface-planted corn This also breaks the soil crust, gives a drier and warmer soil, and a more vigorous crop results Thorough preparation of the seed bed and shallow cultivation make a good combination The harmful effect of letting weeds grow for a time is not entirely due to rapid removal of water and plant-food material by them from the soil but to the breaking of the corn roots in the deeper cultivation necessary for weed eradication

On heavy soils, however, a slight benefit from cultivation other than weed control may be gained by better aeration As the oxygen supply in the soil air is decreased, rate of growth diminishes in a soil with a high temperature [22] For example, corn roots, in a soil atmosphere of 96 4 per cent nitrogen and only 3 6 per cent oxygen, at a temperature of 30°C grow about one-third as rapidly as at the same temperature under normal conditions of aeration But at 18°C , growth is increased to about two-thirds the normal rate at that temperature when the soil is well aerated [21] When one considers the enormous mass of respiring roots, it is clear why an abundant air supply is needed [27] But in most soils the air is changed naturally by diffusion, displacement, renewal due to rains, etc

An examination of the half-grown root system explains why late tillage, except for weed eradication, is of little value The roots

are so well distributed through the soil that little moisture will escape even from uncultivated land. Hilling at the last cultivation not only acts as a mechanical support to the stem but also encourages the development of brace roots which are an additional aid in holding the plant up against strong winds. But, if hilled early, later cultivation partly removes the hill and exposes a portion of the root system. Even shallow cultivation cuts many of the roots and deep cultivation is very harmful and greatly decreases the yield. Cultivation of field corn to a depth of 4 inches during a period of 9 years in Ohio gave a decreased yield every season but one, as compared with similar cultivation to a depth of 1.5 inches. The average decrease per acre was 4 bushels of grain and 183 pounds of fodder.[179] In Indiana, very similar results have been obtained.[90] In Missouri, deep cultivation compared with shallow reduced the yield 6.5 to 13 bushels per acre.[166,54] The harmful effects of deep cultivation are always more pronounced during years of drought. In Illinois where the roots were pruned to a depth of 4 inches at a distance of 6 inches from the hill, the yield was decreased 17 bushels per acre.[109, 181] During a period of 8 years, the average yield of corn in a cultivation experiment in Illinois was 39.2 bushels on plats cultivated three times, 45.9 bushels where no cultivation was given but where the weeds were kept down by scraping with the hoe, and 7.3 bushels per acre on plats where the weeds were allowed to grow.[109] When the plants begin to shade the ground, wind movement is reduced, evaporation is decreased, and the thick network of roots near the surface absorbs the water and prevents its escape into the air.

As a result of a series of cooperative experiments carried on in 28 states during a period of 6 years, it has been found that as large yields of grain were gotten by keeping down the weeds by cutting them at the surface of the soil without forming a mulch as by cultivation.[25] Further analysis of these findings showed that in subhumid or semiarid sections the average yield from the uncultivated land was only 85.9 per cent of that from the cultivated. Thus, the greater need for cultivation in such sections, compared to humid ones, is illustrated. The yields without cultivation, moreover, were found to be relatively higher on sandy loams and silt loams than on clays or clay loams. A difference of 13 per cent was determined between the sandy loams and clays.[109] For the highest yields, cultivation should never be deep enough to injure

the roots seriously. They should be allowed fully to occupy the richest portion of the soil, which is usually the furrow slice. The proper type of cultivation is one which is deep enough to kill the weeds but shallow enough to reduce root injury to a minimum.

Fertilizers.—Hill fertilizing of corn promotes more vigorous early vegetative development with earlier tasseling and earing. The observation of farmers that corn fertilized in the hill sometimes suffers more from drought than when grown in soil where the fertilizer has been uniformly distributed may be explained by a study of root extent in relation to tops. Although no differences were found in the actual abundance, depth, or lateral spread of the roots, the more luxuriant plants resulting from hill fertilizing had a relatively smaller root system.[104] This may also explain why, in Missouri, applying fertilizer in the hill or row yields good returns during seasons of abundant rainfall, but in dry seasons there is more danger that the fertilizer may cause the corn to "fire" than when it is applied ahead of the planter with a fertilizer drill.[54] Because of the extensive development of the roots of practically all cultivated plants, it seems probable that the chief effect of hill manuring is to promote vigorous early growth and that the plant receives little benefit from the manure at the time it is completing its growth and maturing its seed.

Experiments have shown that corn absorbs nitrates and undoubtedly other nutrients at all depths to which the roots penetrate.[174] Competition for water and nutrients from the interlacing roots of plants in the same hill or in adjacent rows is often very severe. These root relations should be considered in the rate of planting especially on less favorable soils and in dry climates.

Suckering.—The removal of suckers or tillers from the base of the sweet-corn plant is a very old practice, formerly followed to a greater extent than it is today. It has been largely discontinued in field-corn culture. Experiments in Nebraska[98,107] and Mississippi[117] have conclusively shown that it materially decreases the yield. The practice is not followed by a large per cent of sweet-corn growers. Experiments at Ithaca, N. Y., during a period of 5 years, show that the removal of the suckers does not accomplish the results usually claimed for this practice, *viz.*, increase of yield, larger yield of high-grade ears, larger size of ear, and earlier and more even maturity. Golden Bantam, which suckers or tillers rather freely, and Stowell's Evergreen, which produces relatively

few suckers, were used in the experiments[159] The data for the 5-year average show a reduced yield from removing the suckers, the greatest reduction occurring when they were removed at the beginning of tasseling The results show, moreover, that removing the suckers reduces the yield of stover, a valuable by-product "Under most conditions the practice of suckering is not justified and is more likely to result in loss than in gain The later the suckering, the greater is the chance for loss"[159] An examination of Figs 4 and 6 will make clear that this is quite what might be expected The larger the sucker at the time of removal the more the balance between roots and stalks would be upset and also the greater the reduction of the food-manufacturing area of the plant.

CHAPTER III

ONION

The common onion (*Allium cepa*) is a biennial with large bulbs that are usually single It is the most important bulb crop and is exceeded in value by only four other vegetable crops grown in the United States, *viz*, potatoes, sweet potatoes, tomatoes, and cabbages Like all the other bulb crops it is hardy and, in the North, is planted very early in the spring In the South it is grown as a winter crop The bulk of the crop is grown from seed sown in the open, but the plants are also grown from transplanted seedlings that have been started under glass or in a seed bed and by planting sets [93]

SOUTHPORT WHITE GLOBE ONION

For root examination the Southport White Globe onion was planted Apr 10 Especial care was exercised to have the soil fine and loose and with a smooth surface, since the seeds are small and do not germinate quickly Thorough preparation of the soil is an essential feature in the successful growth of nearly all crops It is especially important in the production of vegetables The seed was sown in drill rows in the field where the crop was to mature The rows were 14 inches apart and the seed was covered ½ inch deep From time to time the soil was shallowly hoed and all weeds were removed from the plots

Early Development—The onion develops a primary root which, under very favorable conditions, may reach a length of 3 to 4 inches 10 days after the seed is planted In the meantime the cotyledon comes from the ground in the form of a closed loop By the time the first foliage leaf emerges from the base of the cotyledon, several new roots make their appearance near the base of the stem

The first field examination was made June 4 The plants were about a foot tall and had an average of four leaves each These varied from 4 to 12 inches in length and 2 to 5 millimeters in diameter The total area of the cylindrical leaves per plant

averaged 8 5 square inches Each plant was furnished with 10 to 12 delicate, shining white, rather poorly branched roots (Fig 7) The longest usually pursued a rather vertically downward course to a maximum depth of 12 inches The lateral spread from the base of the bulbous stem did not exceed 4 inches The

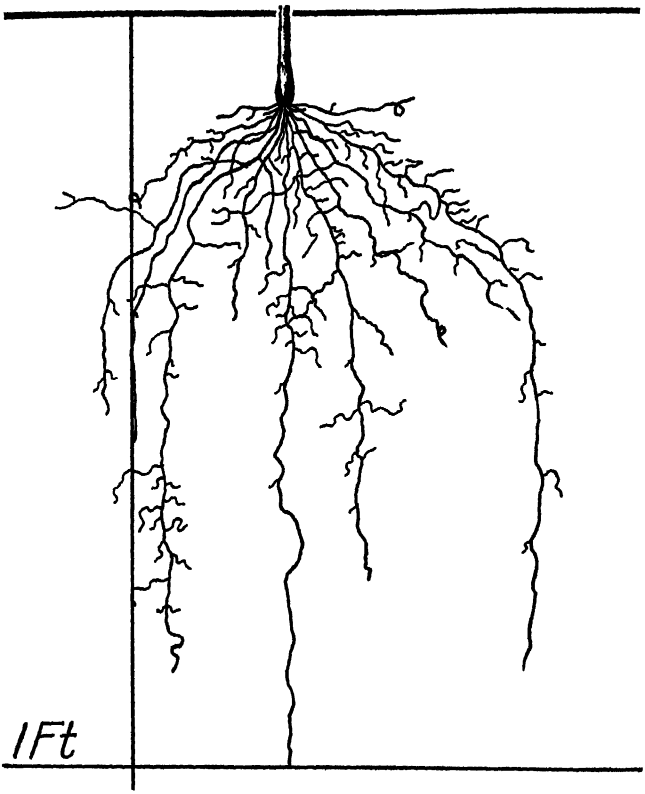


FIG 7—An onion 8 weeks after the seed was planted

roots were rather poorly branched and frequently somewhat curled or pursued a zigzag course

Effect of Soil Structure on Root Development.—To determine the effect of loose and compact soil on root growth, onions were grown in rectangular containers with a capacity of 2 cubic feet and a cross-sectional area of 1 square foot A fertile, sandy loam soil of optimum water content was screened and thoroughly mixed and thus well aerated One container was filled with very

little compacting of the soil It held 173 pounds Into the second container 232 pounds of the soil were firmly compacted Surface evaporation was reduced by means of a thin, sand mulch Onion seeds were planted in each container early in April, and a month later the sides were cut away from the containers and the

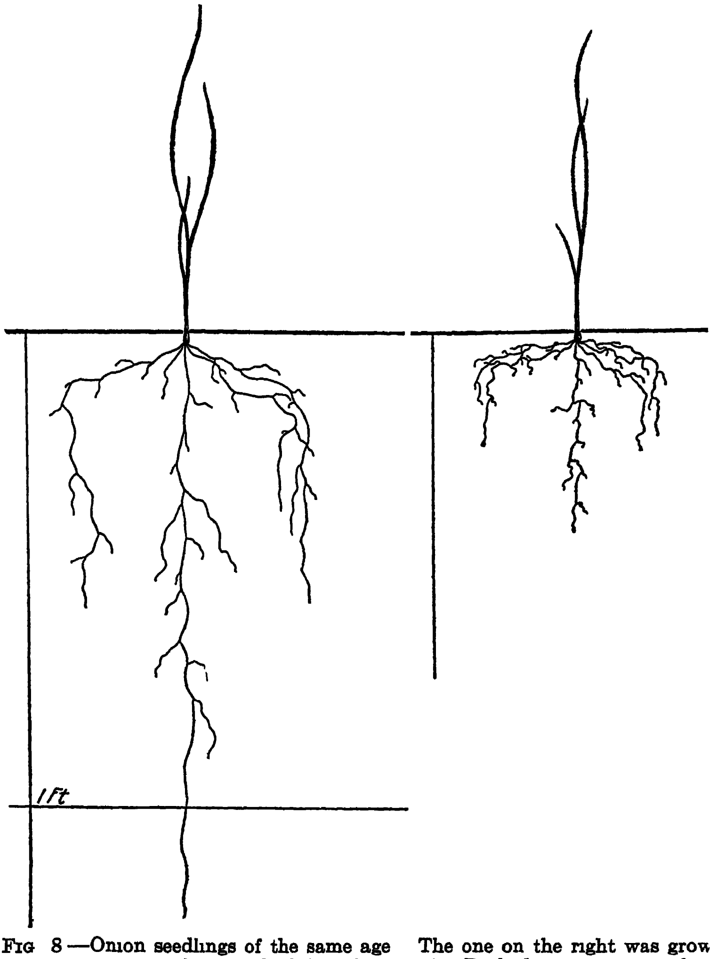


FIG 8 —Onion seedlings of the same age The one on the right was grown in compact soil and that on the left in loose soil Both drawings are made to the same scale

root systems examined Owing to clear weather and favorable greenhouse temperatures the plants had grown rapidly and were in the third-leaf stage

The effects on root growth are shown in Fig 8 In the hard soil the plants nearly always possessed six roots but only five were found on those in the loose soil Under the former conditions the vertically descending roots reached depths not exceeding 5 inches, the others spread laterally 1 to 1 5 inches and then, turning downward, penetrated to a total depth of 2 5 to 3 inches In the loose soil one root from each plant grew downward to a depth of 12 to 15 inches, the others spread laterally 1 to 2 inches and then turned downward and reached a maximum depth of 7 inches Thus the root system in the loose soil was not only deeper but more widely spread The roots in the hard soil, moreover, were much more kinky In the loose soil they made long, gradual curves, in the compact, hard soil, short abrupt ones Under the latter soil condition the root ends were often thickened The roots running laterally from the plant were more horizontal in the hard soil during the first 1 to 2 inches of their course Thus this portion of the root system was shallower than in loose soil Branches were shorter throughout Similar results were obtained with lettuce seedlings (p 322)

Half-grown Plants —By July 25 the bulbs had reached a diameter of 0 5 to 1 8 inches From 28 to 33 roots arose from the base of each of the bulbs, *i e*, at a depth of 1 5 to 2 inches Nearly all of these smooth, shining white roots were a millimeter in diameter although a few were only ½ millimeter thick The longest frequently maintained their initial diameter for distances of 5 to 10 inches, others quickly tapered to a thickness of only ½ millimeter In fact the roots showed considerable variability in this character, sometimes tapering only to enlarge again The deepest roots penetrated vertically downward or ran obliquely outward for only a few inches and then turned downward A working level of 20 inches and a maximum depth of 27 inches were attained

Some of the main roots ran outward, almost parallel to the soil surface, to distances of 6 to 8 inches before turning downward at an angle of about 45 degrees These had a maximum lateral spread of about 12 inches on all sides of the plant Between these horizontal roots and the vertically descending ones, the soil volume thus delimited was filled with numerous roots which extended outward to various distances and then turned downward, or pursued an outward and downward course throughout their entire extent (Fig 9)

As a whole the main roots were poorly branched In the surface 8 to 10 inches of soil branching occurred at the rate of 2 to 6 laterals per inch of main root, although sometimes as many as 12 were found Many of the laterals were only 0 5 to 1 inch long, but some reached lengths of 4 to 5 inches Below 8 inches depth, branches were often fewer and usually shorter, seldom exceeding

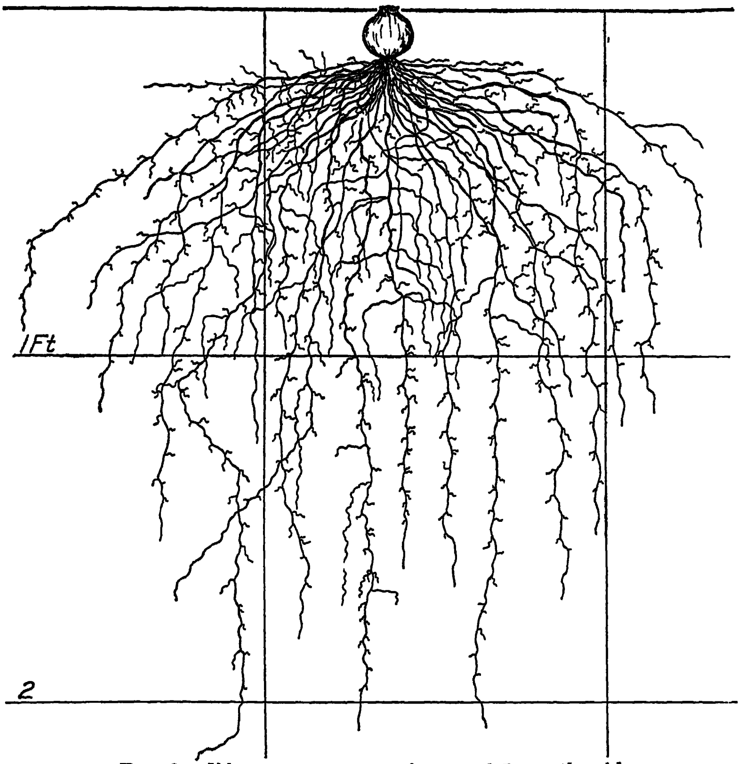


FIG 9 —Fibrous root system of onion, 3 5 months old

1 inch in length The last few inches of the rapidly growing roots were unbranched All of the laterals were slender, white, and entirely destitute of branches Usually they were much kinked and curved and as often extended outward or upward as downward The absence of roots in the surface 1 or 2 inches of soil is an important character in relation to cultivation In this respect the onion is quite different from many garden crops

Mature Plants —By Aug 21 the plants had reached a height of 19 inches Each had four to six leaves which varied in diam-

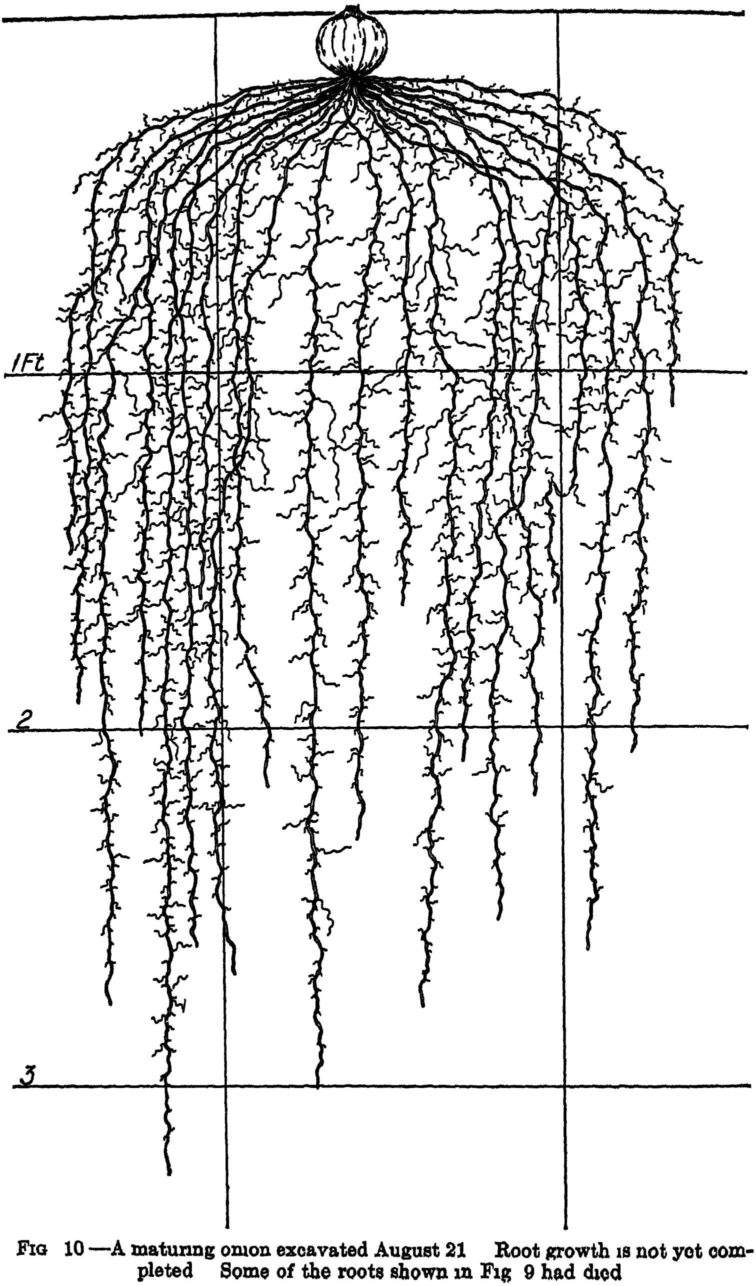


FIG 10—A maturing onion excavated August 21 Root growth is not yet completed Some of the roots shown in Fig 9 had died

eter from 0 5 to 0 75 inch Owing to dry weather the plants were not flourishing and the leaf tips were dry The bulbs averaged about 2 inches in diameter

From 20 to 25 roots arose from the base of the bulb A few ran vertically downward but most of them ran outward at various angles, even to near the horizontal, and then gradually turned downward The volume of soil delimited at the previous excavation (which had an area on the surface of about 4 square feet) had not been increased except in depth The former working level of 20 inches had been extended to 32 inches A maximum depth of 39 inches was found (Fig 10)

The uncompleted root growth was shown by the 2 to 5 inches of unbranched or poorly branched, glistening white, turgid root ends The main roots were very uniform in appearance and about 2 millimeters in diameter throughout their course They were somewhat kinked and curved, perhaps owing in part to the difficulty in penetrating the rather compact soil The branching was somewhat uniform throughout and at the rate of three to five, rarely more, branches per inch These were usually only 0 5 to 1 inch in length although sometimes they reached lengths of 3 to 5 inches No secondary branches were found The laterals, as before, were much kinked and curved Many of them ran in a generally horizontal direction, others extended upward throughout their entire length, still others turned downward or outward and then downward The surface 1 or 2 inches of soil were entirely free from roots Compared with most garden crops the onion has a rather meager root system not only in regard to lateral spread and depth but also in degree of branching

Death of the Older Roots—The decrease in the number of roots from 28 to 33 on July 25 to 20 to 25 on Aug 21 is of interest for it is one of the few cases found among vegetable crops where the roots die before the plant approaches or reaches maturity That death of the older roots originating from the center of the bulb actually occurs was further confirmed by greenhouse studies

Plants were grown from seed in appropriate containers which held 2 cubic feet of soil When the plants were nearly 3 months old (June 23) and some roots had attained a depth of 22 inches, the sides of the containers were cut away and the roots examined From one to three roots per plant arising from the center of the base of the bulb were dead These were surrounded by six to

eight living roots The dead roots, especially one of them, held a more vertically downward course than the live ones

Similar observations have been made in both water and soil cultures "It was observed that the roots formed at the time of germination died at about the time of the formation of the bulb, and that new ones then developed and carried the plants through their complete life cycle" Almost all of the original roots of plants which germinated May 12 were dead 2 months later (2 5 months where grown in soil), at which time the new roots were 5 inches long It is pointed out that the death of the original roots, which come from the older tissue at the base of the bulb, may be due to a number of causes

> (*a*) to the senility of the stem tissues, (*b*) to the senility of the roots proper, and (*c*) to the convolutions which are formed in the tissues of the stem as the result of irregular growth between old and new tissues and which bring about, quite often, disconnections in the water- and food-conducting tissues [13b]

YELLOW BERMUDA ONION

Onions of the Yellow Bermuda variety were studied at Norman, Okla The seeds were sown Mar 16, ½ inch deep, and rather thickly to insure a good stand When the plants were well established they were thinned to 4 inches distant in the row

Early Development—Although growth had been slow yet by May 9, when the first root excavations were made, the plants were 8 inches tall and had four vigorous leaves The root system consisted of 16 to 22 delicate, white, fibrous roots about 0 5 millimeter in diameter They varied in direction of growth from horizontal to vertical The roots were rather lax and their course in the soil wavy The maximum lateral spread was 10 inches and the maximum depth of penetration 12 inches All except the shortest roots were clothed with unbranched laterals which reached a maximum length of 1 inch, becoming shorter near the root ends These were rather evenly distributed at the rate of 2 to 4 per inch The last 2 to 5 inches of rapidly growing main roots were free from branches

Half-grown Plants—A second examination was made June 14 when the plants were 16 inches tall The bulbs were 1 5 inches in diameter and the plants examined had five large leaves The number of roots had increased to 32, the lateral spread to 16

inches, and the maximum depth to 22 inches The roots were also much larger than before, with an average diameter of 1 millimeter which they maintained throughout their course Many of the formerly horizontal or obliquely descending roots had now turned downward at various distances from the bulbs Branching was at about the same rate as before but much more irregular The longest branches reached 2 inches None of the laterals examined were rebranched On some plants the laterals occurred to within 0 5 inch of the bulb, on others an unbranched area of 2 to 3 inches was found The cause for this difference was not ascertained

Growth during the Winter and Second Spring and Summer — Yellow Bermuda onions, left in the field during the dry late summer and fall of 1925, suffered the death of both their tops and root system

By the middle of December, the plants had developed new tops about 3 inches tall These consisted usually of three shoots bearing three leaves each No relation was found between the size of the bulbs and the number of roots to which they had given rise Bulbs 2 5 inches in diameter bore from 28 to 97 roots On a plant with 53 roots their lengths were as follows 9 were 1 inch or less long, 14 ranged between 1 and 10 inches, and the remainder between 11 and 21 inches in length They were 1 to 1 5 millimeters in diameter Their distribution from horizontal to nearly vertical was identical with the root systems already described The distribution of lateral roots was very irregular They occurred only on the longer roots and within 1 foot of the bulb The longest were 2 inches All of the roots were white and rapidly growing

Further examination was made on Mar 9, when the leaves were 6 to 9 inches tall The number of roots varied from 64 to 207 The soil was well filled with roots within a radius of 18 inches from the plants and to a depth of 18 inches A maximum lateral spread of 22 inches and a maximum depth of 33 inches were found Many of these fibrous roots pursued an outward course within 3 inches of the soil surface At distances of 16 to 20 inches from their origin the larger, horizontal roots usually, but not always, turned downward Lateral roots, for the most part, were more or less at right angles to the main ones, but considerable variation occurred They formed a rather complete network of glistening white rootlets to within ½ inch of the soil

surface. Even at a distance of 16 inches from the bulb many were 2 to 4 inches in length but quite unbranched. Nearer the base of the plant laterals 8 to 10 inches long were not infrequent. All of the primary laterals, except a few of the longest, were devoid of branches.

By June 20 the plant had an average height of 40 inches, although some exceeded this by 1 foot. Since each bud on the original bulb had developed into an individual plant, a hill now consisted of two to five plants with bulbs 2 inches in diameter but still loosely united by the crowns. In part the heads consisted of many flowers in full bloom but mostly of nearly mature seed pods.

Each stalk was furnished with 32 to 48 roots, the strongest and most profusely branched of any yet observed. Many were 3 millimeters in diameter, often retaining a thickness of 2 millimeters throughout their course. The roots, however, had extended their area of occupation but little—to a maximum lateral distance of 22 inches and to a depth of 34 inches. This lack of linear growth had been met in two ways. New roots had replaced some of the older ones which had died and the branches throughout were longer and more profuse than heretofore. In fact the whole root system from near the bulb to within a few inches of the root tips was well supplied with branches. Many of these were 1 millimeter in diameter and frequently 10 to 12 inches in length. Occasionally, they bore sublaterals. These were never abundant. On a few roots they were found to occur at the rate of two per inch throughout a distance of 3 or 4 inches. They were about 0.5 millimeter in diameter and averaged about ½ inch in length.

Summary.—The onion has a fibrous root system consisting of 20 to 200 shining white, rather thick roots. Some of these spread horizontally just beneath the surface soil 12 to 18 inches on all sides of the plant before turning downward. The soil area to be occupied is blocked out by the plant rather early in its development, and later growth consists chiefly in root elongation. In compact soil the roots are shorter, do not spread so widely, and have shorter branches than in loose soil. The rate of root growth of the Southport White Globe onion is shown in Table 10. Depths of 18 to 32 inches are usual. The roots are poorly furnished with rather short laterals which are usually unbranched. As the older, centrally placed roots die, they are replaced by

TABLE 10.—RATE OF ROOT GROWTH OF ONION

Age, days	Lateral spread, inches	Working depth, inches	Maximum depth, inches
55	4	10	12
106	12	20	27
133	12	32	39

peripheral new ones. Compared with most garden crops, the onion has a rather meager root system not only in regard to lateral spread and depth but also in degree of branching.

Other Investigations on Onions.—At Geneva, N. Y., onions of the Blood Red variety were examined in the middle of September. The plants were grown in a fertile, clay loam soil overlying a tenacious, gravelly clay subsoil. It was found that

> the root system is by no means extensive but it is very much concentrated. The roots seem to take complete possession of the soil beneath a circle about 8 inches in diameter to a depth of about 10 inches.

Very few roots penetrated beyond these limits. A few spread horizontally 10 inches from the bulb. The laterals are never rebranched.[43]

The roots of the Large Red onion were washed from the soil at the same station on June 21. The leaves were but 8 inches long and the bulb only a few millimeters thick, but the roots were found to extend to a depth of 16 inches. Further examination, in September, showed that most of the roots extended no deeper than at the June examination. In a few cases roots were found at a depth of 18 inches but no horizontal roots could be traced farther than 1 foot.[44]

> The roots radiated from the base of the bulb in all directions below horizontal, some lying no more than 1 inch beneath the surface. They were of equal size throughout their length, except that they were slightly swollen close to the terminus. New roots appeared to be growing, as some were decidedly shorter than the others. The branches were all short and never subdivided.
>
> In order to note whether the root growth in this plant the second year differs from that of the first, the roots of a plant of which the full-grown bulb was planted out in the spring were washed out June 10. The system was the same, in general, as that of the first year. An estimate made it probable that the plant had formed at least 400 feet of roots and root branches, though it had been set out but about 40 days.[44]

Very few roots of onions grown on gravelly sandy loam soil at Ithaca, N. Y., reached a depth of more than 10 inches. A few were found as deep as 20 inches. The greatest lateral spread was 12 inches but few reached out more than 6 inches. The main root zone was found within a radius of 6 inches.[152]

The growth of seedling Yellow Globe onions at the same station was as follows: "At the time when the onion seedlings were set out, each plant had about ten to twelve roots averaging about 3 inches long. Twenty-five days after the plants were set in the field, the roots had reached a depth of only about 2 inches and had a lateral spread of 3 inches. At this time there was an outer whorl of about ten to fourteen coarse roots without branches. Inside of this whorl were about twelve to fourteen finer roots with a few short branches. These smaller roots grew downward. Twenty days later, when the plants were 12 inches tall and a little larger at the base than a lead pencil, the roots had reached a depth of 4 inches. At this time there were about ten to twelve roots growing vertically downward and about twenty-two to twenty-four larger lateral roots extending from 3 to 4 inches from the plant. Ten days later a few roots had reached a depth of 10 inches and a lateral spread of 6 inches, although most of the growth was within from 3 to 4 inches of the plant. At this time there were about twenty-eight to thirty coarse roots with a very few short branches, and twelve finer roots, each having several branches, growing downward from the base of the plant. When the bulbs were 2 inches in diameter the greatest depth reached was 18 inches and few had gone lower than 12 inches. The greatest lateral spread was 9 inches, with very few roots extending to more than 6 inches from the plant. At this time there were thirty-six coarse roots at the base of the outer scales and twelve finer-branched ones growing out of the center of the bulb at the base. When the bulb was full-grown a few roots had reached a depth of 20 inches, but most of them were in the surface 6 to 8 inches of soil and within a radius of 6 inches. Many roots were found very near the surface, especially close to the plant, but the greatest number were found at a depth of from 2 to 3 inches. The tendency of growth of the outer whorl of roots is outward and downward for a few inches, and then nearly vertically downward. The main root zone was within a radius of 6 inches ... which leaves a space of 6 inches between the rows with few or no roots."[159a]

Relation of Root System to Cultural Practice —The relatively meager root system and correspondingly limited extent of above-ground parts explain why onions can endure crowding better than most vegetable crops Plants thrive when grown only 3 to 4 inches apart in rows 12 to 15 inches distant In fact close planting increases the yield [182] The concentration of the roots into a relatively small area helps to make clear the marked response to fertilizers worked into the surface soil and also why a very fertile soil is necessary for abundant yields

Few crops require such thorough seed-bed preparation as does the onion and this is undoubtedly due in part to the poor rooting habit of the seedlings The roots have difficulty in penetrating stiff clay soils and this is one reason why such soils are unsatisfactory unless there is sufficient humus present to lighten them Neither are the plants adapted to a light, open, gravelly soil, as the roots must grow in a continually moist soil, a good supply of water being especially necessary during early stages of growth A soil retentive enough to keep a constant supply of moisture about the roots but friable enough to permit expansion of the bulbs and easy root penetration is ideal

The present-day tendency to sow the seeds more thinly and dispense with thinning is certainly a logical practice as regards the lack of disturbance of a poorly branched root system Pulling out plants in the process of thinning undoubtedly disturbs the root system and breaks many of the roots of those left in the rows Thinning when the soil is moist causes less harm In fact one of the most harmful effects of weeds may be not so much that of shading or absorbing nutrients and water which should be used by the crop as that of root disturbance of the cultivated crop occasioned by their removal If the root system is thus much disturbed, the onions are likely to ripen prematurely before reaching normal size

Weeds should be destroyed as soon as they appear above the soil surface, for then their roots are poorly established The lack of the dense network of laterals, associated with the roots of most vegetable crops, probably accounts for the need of an especially well-prepared, deep seed bed and the inability of onions to compete successfully with weeds Actual practice has shown that to produce a good yield of onions the weeds must be kept under control and a surface mulch be maintained to conserve moisture

For many densely rooted crops, experiments in New York have shown that cultivation for the purpose of moisture conservation is not profitable[152,158,159a] Corn, for example, has such an extensively developed network of roots in the surface as well as in the deeper soil (Figs 4 and 6) that the roots absorb the moisture before it reaches the surface[25,135] Likewise, carrots, beets, cabbage, and beans, all deeply and densely rooted plants, show very little or no advantage in cultivation, as regards moisture content of the soil, over those in plats where the weeds were removed by scraping the surface soil Although a difference of only about 1 per cent more moisture was found in the plats cultivated once a week, the yield of onions was greater than in plats where the soil was scraped to keep down the weeds In these experiments, on a gravelly sandy loam, the onions were grown in rows 18 inches apart and 4 inches distant in the row. Since, in this experiment, the main root zone was within 6 inches of the plant, a space 6 to 12 inches wide between the rows contained very few roots Moreover, since the tops shade the soil but little, it may be clearly seen how a soil mulch resulting from cultivation would conserve the soil moisture The roots are not so superficially placed as to be injured by shallow cultivation

There is apparently a correlation between the extent and distribution of the root system and the response of the crops to cultivation for purposes other than the destruction of weeds, moisture being conserved by cultivation for plants like the onion with meager root development[152,158] Thus it would seem that the usual distance between the rows, about 14 inches for hand cultivation and 18 to 24 inches for cultivation with a horse-drawn cultivator, is quite ample for full root development with little or no competition between plants in adjacent rows In fact the bulb crops are about the only vegetable crops for which this statement is true

When onions are transplanted in the "new onion culture," it is usual to trim both tops and roots to a considerable extent Trimming the tops reduces the transpiring area and makes reestablishment more certain The roots are trimmed to facilitate planting and to avoid having any long roots curl upward

In growing onion sets, the older practice was to sow the seed late in the season on poor soil Lack of sufficient water and nutrients, resulting in part from thick planting, combined with hot weather, resulted in the desired small bulbs Now many

commercial growers depend upon competition alone. Seeds are sown very thickly on rich soil, often 200 per foot of drill. The rows are spaced only about 1 foot apart. Under these conditions, it is impossible for the competing roots to make a normal growth and secure enough water and nutrients to supply the top which is dwarfed as a result. Consequently, the bulbs never become very large.[93]

CHAPTER IV

LEEK

Leek (*Allium porrum*) is a very robust, biennial plant Bulbs are nearly always absent, the plant being grown for its blanched stems and leaves The plants are propagated entirely from seed which is sometimes sown in the greenhouse or hotbed and the seedlings later transplanted into the field

Early Development—Leek of the Large London variety was planted at Norman, Okla, Mar 16 The seeds were thickly sown to insure a stand, and later the plantlets were thinned to 4 inches distant in the rows which were 3 5 feet apart Weather conditions were not favorable for germination or growth, and the plants developed slowly When they were nearly 2 months old (May 19) and had reached a height of 10 inches, the first root examination was made Each plant had four leaves approximately ½ inch in width

An average of 16 roots, in all stages of development, was determined per plant As a rule, three were less than 1 inch long, four were 6 inches or less in length, the remainder grew to lengths of 7 to 14 inches Their direction of growth was very similar to that of the onion, although, in general, they spread to a greater extent (Fig 11) A maximum lateral spread of 8 inches and a depth of 14 inches were found The white, tender roots were free from abrupt turns and short curves but pursued a rather wavy course through the mellow soil They were 1 millimeter thick and the older ones had given rise to short laterals at the rate of about two per inch

Half-grown Plants—From this time the plants grew rapidly, owing to a favorable supply of soil moisture By the middle of June they were 15 inches tall, possessed bulbs 0 5 to 0 8 inch thick and leaves 1 inch in width The roots had increased in number to an average of 38 per plant Most of them ran 6 to 8 inches more or less horizontally outward and then downward, the others ran obliquely or, frequently, nearly vertically downward (Fig 12). A maximum spread of 14 inches was attained at a

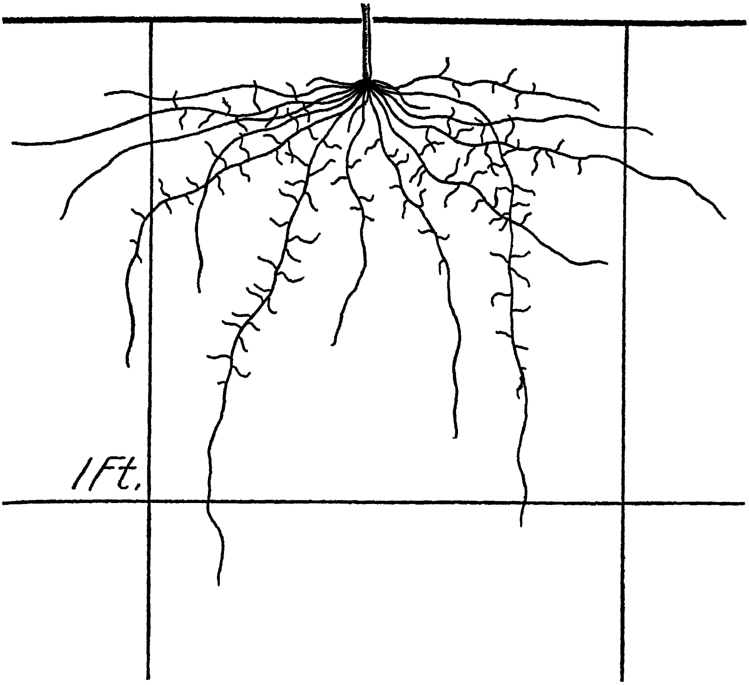


FIG 11 —Roots of a two-months-old plant of leek

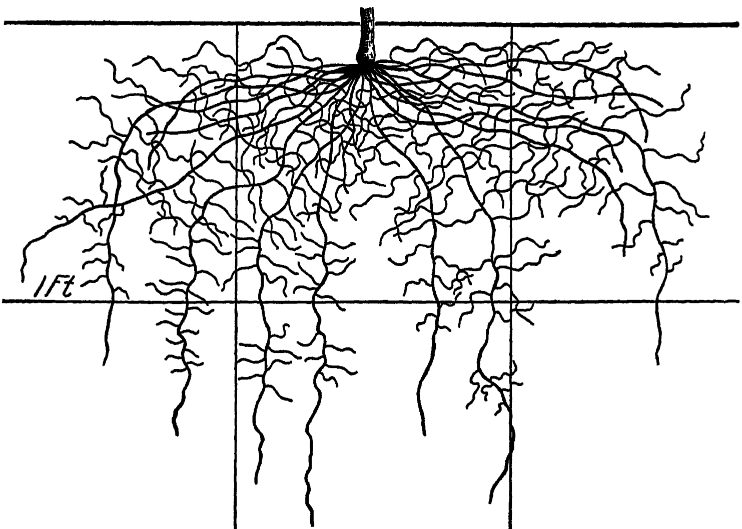


FIG 12 —One-half of the root system of leek, 3 months old

depth of 6 to 8 inches and some of the vertical roots reached a depth of 20 inches. In penetrating the more compact subsoil, the roots often pursued a tortuous course and were more kinked than in the first 8 inches of mellow soil.

Maturing Plants.—The leek plants were in fine condition and still growing vigorously on July 26 at the final examination. Each had about a dozen leaves, the largest being 2 to 2.5 feet long and 1.5 inches wide at the base.

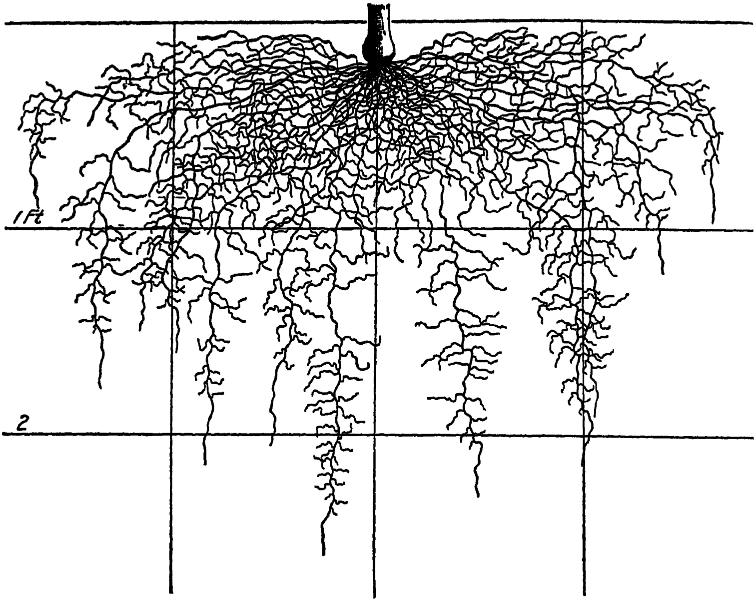


FIG. 13.—Leek late in July of the first season's growth. The root system was still developing vigorously and would probably have extended much deeper. Only about one-fourth of the roots are shown.

A typical plant had 119 fibrous roots extending in all directions from the base of the stalk from horizontally to vertically downward. Many of these roots were only 1 millimeter in diameter but the larger ones were 1.5 millimeters thick, at least throughout the first foot of their course. The general direction of growth may be seen at a glance (Fig. 13) where it may be noted that the lateral spread had been increased to 21 inches and the maximum depth to 30 inches. A comparison of Figs. 12 and 13 shows that not only is the surface foot very much more thoroughly ramified by the root network but also that the second foot of soil is thor-

oughly occupied Indeed, the 12- to 24-inch level was now the seat of great activity and it seems almost certain that in later stages of development similar root activity might be found in the deeper soil

Tiny laterals usually began to appear about 2 inches from the root tips These increased in length on the older portions of the root, reaching a maximum of 2 inches a foot from the root ends On some of the roots, branches occurred quite irregularly Thus considerable portions of the roots were free from laterals On others an almost uniform distribution of two rootlets per inch was found throughout their length On the larger roots, within a radius of approximately 12 inches from the base of the plant, larger branches occurred Frequently, a length of 10 inches was attained by these laterals, which were, however, only rarely rebranched The number of laterals per inch of main root had not increased but they were longer than before and occurred over a much larger root area

Summary —Leek has a fibrous root system which consists of 50 to 100 or more main roots Many of these spread 14 to 21 inches just beneath the soil surface where they may end or, more usually, turn downward Others pursue an obliquely downward course so that the soil is ramified with roots of mature plants to a depth of 18 to 24 inches The branches are moderately few with a maximum length of 10 inches but they rarely rebranch

Compared with the onion of equal age the root system of leek spreads more widely, a fact that may be correlated with the practice of spacing leek plants a little farther apart than onions Otherwise cultural practices are similar The top development of leek is also considerably greater than that of the onion The depth of penetration is much less but this is partly compensated by the much longer laterals and the more thorough distribution of roots in the surface soil More profuse branching and more thorough occupancy of a wider area of soil have also been found by other investigators [89] In both species the laterals are only rarely rebranched To what degree these differences are heritable and to what extent they may be modified by environment await experimental investigation

CHAPTER V

GARLIC

Garlic (*Allium sativum*) is a hardy, perennial, bulbous herb closely allied to the onion. Unlike the onion which usually produces one large bulb, garlic bulbs are composed of several, small, elongated, egg-shaped bulbils, all of which are enclosed in a whitish skin. In propagation these bulbils or cloves are more commonly used than seeds.

Strong cloves were planted Oct. 1 at Norman, Okla., in double rows 6 inches apart. The cloves were spaced 12 inches apart and a distance of 30 inches was left between the double rows.

Early Development.—Owing to favorable weather the plants made a rapid growth and by the middle of December the tops consisted of about five leaves per plant. These were approximately 1 inch in diameter and 6 inches long. They had developed about 18 roots per plant. Most of them spread horizontally at a depth of 2.5 to 5 inches, a few grew nearly vertically downward, and the remainder took an intermediate direction of growth. They pursued a rather zigzag course through the soil, often turning sharply or forming a complete coil where a clod or other obstacle was encountered. A maximum spread of 9 inches and a depth of 11 inches were attained. Roots that did not exceed a length of 8 inches were destitute of laterals. Older and longer roots were furnished with a few branches 1 inch or less in length. These occurred on all but the youngest one-third of the roots but there were only one to two per inch. The main roots were about 1 millimeter in diameter and very tender. The characteristic alliaceous odor could be readily detected to very near the root ends.

Growth during the Winter.—On March 1, just after spring growth had begun, a further study was made. Since no freezes of sufficient severity to kill the tops had occurred, the plants grew during the winter. There were five to six well developed leaves, 6 to 8 inches long, per plant.

The number of roots varied from 25 to 50 depending upon the size and vigor of the plant. The lateral spread had been increased

to a maximum of 15 inches and the depth to 22 inches Although some of the horizontal roots still ended at about the same depth as their origin, many, after extending laterally 8 to 12 inches, turned downward 1 to 3 inches The direction of growth of the other roots had not changed All remained white in color and about 1 millimeter thick Within 1 foot from the bulb, laterals were numerous The longest ones extended 1 5 inches, often toward the soil surface Farther from the base of the plant, they became fewer and shorter The rapidly growing, shining, white root ends were free from laterals

Mature Plants.—By June 12 the plants were 2 feet high and well developed clusters of sets had formed The yellowish leaf tips and the general maturity of the plant indicated that they had nearly completed their growth The group of bulbs at the base of the plants averaged 1 5 inches in diameter There were now 40 to 60 roots per plant, some of which extended 18 inches laterally, others penetrated to a depth of 2 5 feet Some of the main roots had grown to 1 5 millimeters in diameter near the plant Laterals on these, 8 inches long near the bulb, were not infrequent Many extended upward in such a manner that the shallowest main roots were 2 to 3 inches deep but the surface soil was thoroughly ramified All of the laterals were longer than formerly and although not abundant on any one root, yet so many main roots ran through the soil that it was well occupied At this time the roots did not appear to be growing vigorously As in its earlier stages of development, the root system was very similar to that of the onion and the leek

An isolated 2-year-old plant had an even more extensive root system which correlated with a better developed top The latter consisted of 32 stalks Each stalk had an average of 25 main roots, 1 5 millimeters in diameter This thickness was maintained throughout the entire length of the white, succulent roots A lateral spread of 22 inches, 4 inches greater than that previously found, and a depth of 40 inches were ascertained The roots were, moreover, growing rapidly The soil was densely filled with a network of roots The well-developed laterals typically occurred at the rate of two per inch but not infrequently they were lacking for several inches along the root

Summary.—The root system of garlic is very similar to that of the onion and the leek The number, size, direction of growth, and length of the main fibrous roots are very similar A maxi-

mum lateral spread of 18 inches and a depth of penetration of 2 5 feet are attained during the first year The rate of occurrence of the simple laterals is also similar to that of the leek and the onion but the branches are somewhat longer than in the onion The thorough occupancy of the surface soil was as pronounced as that in the growth of the leek and somewhat more so than that in the growth of the onion This difference may be due to differences in soil environment

The similarity of both roots and tops of garlic and leek to the onion explains why similar cultural practices apply to all three species of bulb crops

CHAPTER VI

ASPARAGUS

The common garden asparagus (*Asparagus officinalis altilis*) is a perennial plant with much branched, annual, aerial stems which reach heights of 3 to 10 feet These, like the long, somewhat fleshy, cord-like roots, arise from a rather short, much thickened, branched, and rather woody rootstock or crown which lies in a horizontal position a few inches below the soil surface This rootstock grows 1 to 3 inches a year, either at one or both ends, hence, an asparagus plant once established will produce for many years Asparagus is one of the most popular of the perennial vegetable crops It is grown on a vast scale commercially and an asparagus bed is to be found in most home gardens The plants are grown for their thick, soft, young shoots which appear early in the spring

Early Development—The early growth of asparagus has been thoroughly studied in California

> In the growth of the seedling, the single, primary root takes a direct course downward, developing numerous thread-like lateral rootlets The chief function of this primary root with its laterals is absorption It seldom attains a length of more than 5 or 6 inches It is much more slender and fibrous than the storage roots which develop later The single primary shoot takes a direct course upward and upon reaching the light develops a few side branches and leaves This primary shoot seldom attains a length of more than 4 or 5 inches Both the primary root and the primary shoot are temporary organs They wither and die long before the end of the growing season The primary root and primary shoot attain a length of 3 to 4 inches before connection with the reserve supply of food in the seed is severed On the very young crown a brown scar may be observed at the point where the absorbing organ was attached[71] (Fig 14)

Table 11 shows the rapidity of development of both roots and shoots Both primary shoot and primary root were withered by Aug 13.

The rapid development of storage roots both in number and length is of interest If they continued their growth in length at the same rate after midsummer as in July, *i e*, nearly ½ inch per day, a depth of 3 5 feet would have been attained Even

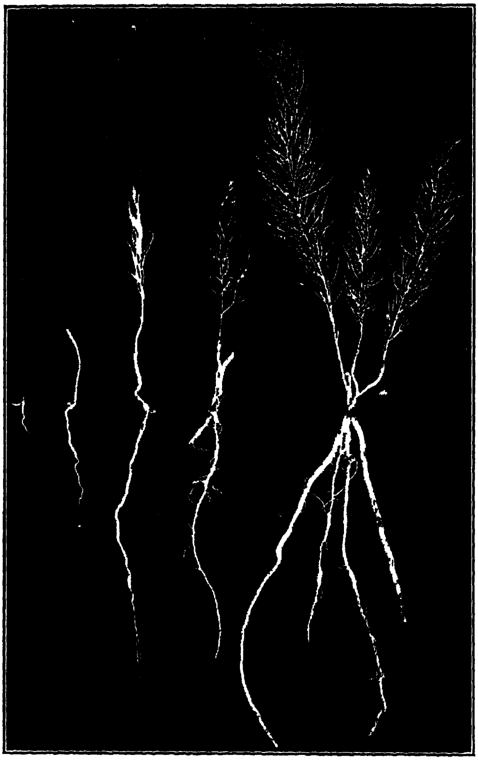


FIG 14 —Five stages in the development of an asparagus seedling At the left a very young stage showing the short seminal root and the much shorter seminal shoot, both of which are attached to the seed and are deriving nourishment from the stored food in the endosperm In the second and third stages the seed is still attached In the fourth stage the plant has become independent of stored food in the seed, the seminal shoot has branched slightly, a second shoot has arisen from the crown, and a fleshy root has developed In the fifth stage there is shown the seminal shoot, two well-developed, secondary shoots and one very short secondary shoot The ages of the seedlings in days are 10, 14, 34, 54, and 75, respectively (*After Jones and Robbins, Calif Agr Exp Sta*, *Bull* 381)

an accelerated rate of elongation in late summer is not improbable, since the shoots are large enough to furnish much food Although the plants produced but a single secondary shoot after

TABLE 11 —DEVELOPMENT OF ASPARAGUS PLANT DURING FIRST SEASON[71]
(Numerical values are the average of 20 plants Seeds planted Mar 24)

Date of observation	Length of primary shoot above the seed, inches	Length of primary root, inches	Number storage roots	Maximum length storage roots, inches	Number secondary shoots	Maximum length secondary shoots, inches
Apr 27	3 0	4 1	0 0	0 0	0 0	0 0
May 19	3 8	5 1	1 6	0 2	1 2	1 1
June 9	4 0	5 2	4 1	5 5	2 1	5 7
June 30	4 2	5 4	6 4	7 5	3 7	7 6
July 24	4 3	5 4	16 1	18 6	5 5	12 1
Aug 13			28 3		8 1	20 2
Sept 20			42 0		9 0	24 0

Aug 13, there was, nevertheless, a considerable increase in the number of storage roots and in the size of the crown

The storage roots are clothed with fine, fibrous, often unbranched, absorptive roots which extend throughout their course The fleshy roots increase in number, growing out from the sides and under surface of the rootstock They continue their growth in length from year to year Frequently, a definite scar may be found where the renewed growth occurred Thus a very widely spreading and deeply penetrating root system is produced

Mature Plants —The common garden asparagus was excavated and studied near Lincoln late in June The plants had been growing in the field about 6 years The tops were 4 feet tall and the fruits fully grown but green The black silt loam soil of loessoid origin was about 16 inches deep and underlaid with a very stiff clay The clay continued to a depth of 3 5 feet below which it gradually gave way to loess The soil was quite dry, at least to a depth of 9 feet, and made root excavations difficult

The long, fleshy storage roots arose from a rootstock or crown which occurred at a depth of about 6 inches (Fig 15) The fine, fibrous, absorptive roots occurred mostly as branches on the fleshy ones The branched, rather woody rhizomes were about 1 inch thick and frequently many inches in length, the older portions having rotted On a section of rhizome only 6 inches long, 140 roots were found (*cf* Fig 16) These were 4 to 5 millimeters in diameter and extended in all directions except toward the soil surface It is quite impossible to show all of the roots in a small-scale drawing

Some of the roots radiated horizontally from the rhizome 4 to 6 feet or more, at depths of only 3 to 8 inches Although they were 4 to 5 millimeters in diameter, they gradually tapered toward

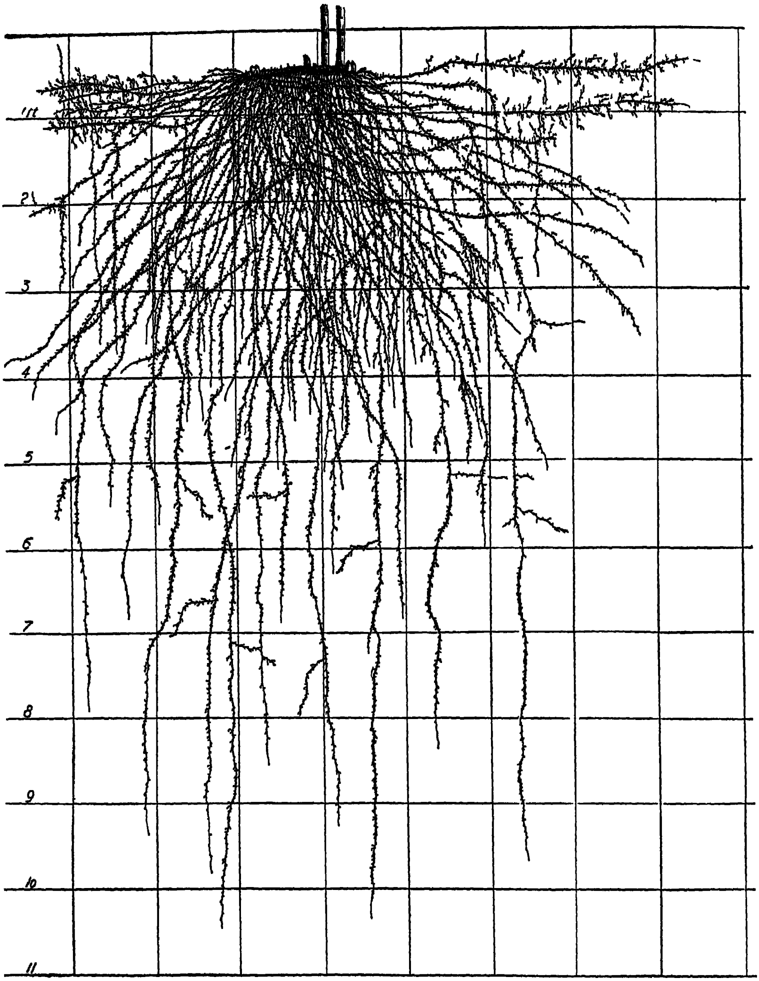


FIG 15—Rootstock and root system of a 6-year-old asparagus plant Not all of the very numerous main roots are shown

their ends where they were only 2 millimeters thick They were much more branched near their extremities than close to their origin For example, in the first 2 to 3 feet of their course, three

to five rootlets per inch about 0 3 inch long and quite unbranched, were found But on the distal half there were usually five roots per inch, most of which were rebranched These roots were from 1 to 4 inches long and formed quite a network in the surface soil They were rebranched at the rate of two to five rootlets per inch, these secondary branches varying from 0 1 to 1 inch in length.

In addition to the horizontal, widely spreading roots, numerous others pursued an obliquely outward and downward course before

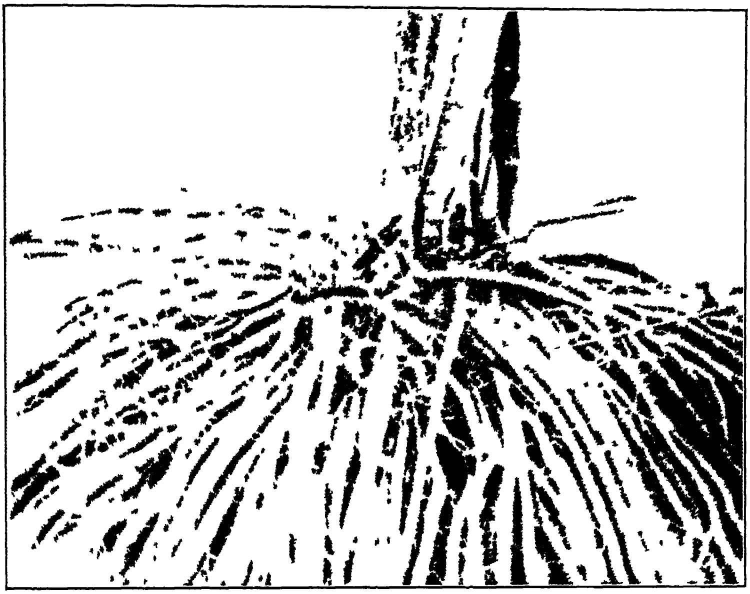


FIG 16 —Crown and roots of a 3-year-old asparagus plant (*After Brooks and Morse, Mass Agr Exp Sta Bull* 194)

penetrating straight downward Still others ran almost vertically downward They showed many kinks and curves in penetrating the clay soil layer These roots were rather poorly branched at the rate of no laterals to five per inch Most of the branches were short, 0 2 to 1 inch in length, and only occasionally did a branch several inches in length occur The longer branches were rebranched at the rate of two to three rootlets per inch

Branching was most abundant in the surface foot of soil where the white tender branches formed a dense network This is very difficult to illustrate in a small-scale drawing In fact, it appeared that most of the absorption was carried on in the surface 3 feet of

soil and especially in the surface foot. The working depth, however, as indicated by the abundance of roots, occurred at 4.5 feet, although some large roots extended deeper, and the maximum penetration was 10.5 feet.

Between 3 and 4.5 feet, roots with a diameter of 1 to 2 millimeters were abundant and a number of the larger roots (5 millimeters thick) ended here. The thicker roots were somewhat better branched than the finer ones, the branches were longer and more of them were rebranched. Below the working depth roots were not numerous. They were 1 to 2 millimeters thick, 0.2 to 1 inch long, and occurred at the rate of no roots to five per inch. Like other short branches on the main roots, they were simple and mostly horizontal but sometimes quite kinky. Occasionally, a rebranched lateral 3 to 5 inches long was found. Nearer their ends, *i.e.*, below 9 feet, the main roots were only 1 millimeter or less in diameter. The smaller ones had few or no branches, the larger ones had fewer and shorter branches than those just described. The roots at this depth were usually found in earthworm burrows or in the holes formed upon the decay of previous roots. Frequently, they ran horizontally for a number of inches along these lines of least mechanical resistance in the richer and better aerated soil. Numerous cases were observed where the main roots had ceased elongating at various depths, especially those growing in the stiff clay. Then branches had arisen just above the large root cap and extended for several feet into the soil. These branches had a much smaller diameter than the main roots. The latter, arising from the rhizome, tapered very little toward their ends.

The finer roots were white in color, fleshy, and very brittle, thus being very difficult to excavate from the rather dry soil. Dead roots in all stages of decomposition were found, occasionally between depths of 8 and 10 feet. They were especially abundant in the surface soil, often consisting of the corky exterior and a small brown or black stele in the center, the food-stored, watery portion of the cortex decaying rapidly.

Summary.—Asparagus is a perennial plant with a very extensive root system, which arises from a thick rootstock which grows from year to year. The primary root is only a few inches long and is short lived. It is soon replaced by the thick, long, storage roots which are clothed with short, absorbing laterals. The root system, under favorable conditions, may extend to a

depth of 3 feet or more during the first season of growth With the growth of the rhizome, the roots greatly increase in number Many radiate into the surface soil 4 to 6 feet even in compact silt loam Others grow outward and downward and then pursue a vertically downward course Finally, numerous roots grow almost vertically downward Thus a very large soil volume is occupied to a working depth of 4 5 feet Some roots are 9 to 10 5 feet long Branching is, however, most abundant, and undoubtedly absorption is very active in the surface foot of soil

Other Investigations on Asparagus —Asparagus plants about 3 years old were examined at Geneva, N Y The soil was a clay loam underlaid at a depth of 6 to 10 inches with a tenacious, gravelly clay subsoil The longest roots were more than 2 feet deep and others extended horizontally an equal distance

> The greater part of the feeding ground of the roots seemed to be within 15 inches of the surface, though many roots extended below this Roots penetrated beneath an area 5 feet in diameter [43]

These findings are scarcely in agreement with the preceding or the following investigations

Three-year-old asparagus plants, grown at Concord, Mass , on coarse, sandy loam were taken for chemical examination and without particular reference to securing the entire root system They had an average root length of 4 feet and a few roots 5 5 feet long were recovered [16]

Another writer states

> many of the individual storage roots, in a plant 8 or 9 years old, may extend to a depth of 6 to 8 feet and laterally to a distance of 8 to 10 feet The great mass of storage roots, however, is confined to the surface 3 feet [118]

Habit of Underground Parts in Relation to Cultural Practice — A few of the more important ways in which the roots and rhizomes of asparagus are closely related to the common practices in the successful production of the crop will be briefly discussed

Soil Preference —That asparagus grows well in almost any kind of soil is indicated by its success as a weed when it escapes from cultivation A consideration of its root and rhizome habit makes clear why a deep, loose, light type of soil is best Open, porous soils permit of easy penetration and elongation of the rather thick storage roots Such soils, moreover, warm earlier

in spring and promote a more rapid, early growth These soils are well drained, an essential environmental factor for good development, since asparagus roots are very sensitive to an excess supply of water which reduces soil aeration

Another important factor is that connected with the practice of propagating the plant by resetting the crowns and attached roots from plants grown from seed in the nursery In light soils the crowns may be dug with a minimum of injury Heavy soils become packed and it is difficult to dig the crowns without injuring many of the rootstocks and losing a large percentage of the fleshy roots [71] These roots contain the reserve food supply and loss of them lessens the early growth of the plant

Transplanting —The preference by practical asparagus growers for 1-year-old plants, rather than more mature ones, is undoubtedly related to the extent of root development With asparagus, as other plants, transplanting checks growth If the growing point of a fleshy root is uninjured in transplanting it will continue to elongate Transplanting, however, permits of the selection of the most vigorous plants and also has certain other advantages, especially that of getting a full stand of the crowns started at a proper depth In the process of transplanting, the roots are spread out evenly on the bottom of the trench or over a small mound of earth placed thereon and moist soil packed firmly about them [49]

Sowing the seeds in pots and starting the plants in the greenhouse or hotbed, repotting into larger containers, and finally transplanting into the asparagus bed without root injury should promote vigorous development of the plants and increase the succulent stem development earlier in the life of the plant [151] Experiments in Pennsylvania, extending through a period of 6 years, have shown that the size of the transplanted roots has a direct relation to subsequent yield The larger, more vigorous plants bore crops with a 26 per cent greater value than the smaller ones[4] (Fig 17) In the process of transplanting, the roots and crowns should not become desiccated or the resumption of growth will be greatly delayed

The practice of planting the crowns deeply, although not covered to the extreme depth until the shoots are well up, is directly connected with the root habit Many of the old fleshy roots die each year and are replaced by new ones The new roots originate from the rootstock at points somewhat higher than the

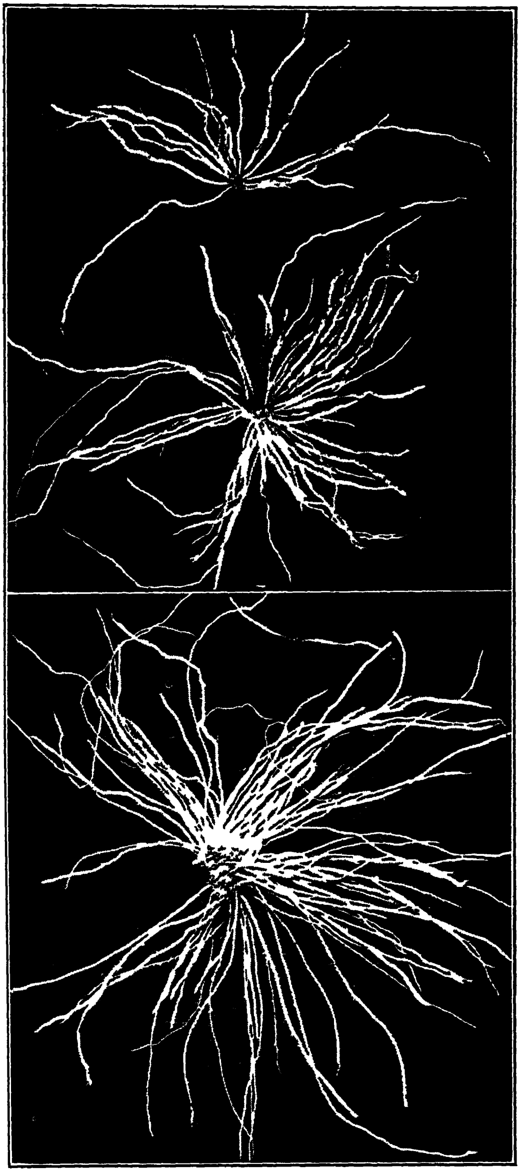


FIG 17 —Grades of crowns "Number 1" (bottom), "Number 2" (center), and "Number 3" (top) It should be the aim of the grower to produce "Number 1" crowns to plant in the permanent field (*After Jones and Robbins, Calif Agr Exp Sta, Bull* 381)

older ones and thus each year approach nearer the soil surface To compensate for this so-called "lifting of the plants," the crowns are placed at least 8 to 10 inches deep Otherwise in only a few years they would be injured by the process of cultivation Beds planted too shallowly may last only a few years, plants in deeply planted and properly cultivated and fertilized beds retain their vigor for 10 to 20 years [151] In all tillage operations constant care must be exercised to prevent injury to the rhizomes and roots

Growing the Seedlings —In planting asparagus seeds they should be spaced a few inches apart Where the seeds are dropped in groups, fleshy roots and rootstocks become so interwoven that they are separated with difficulty and often with considerable injury to the plants If thinning is necessary it should be done before the second aerial shoot has appeared and before the development of the fleshy root system has begun

After the fleshy root system has begun to develop, the shoot usually breaks at the crown when an attempt is made to pull the plant after the fleshy roots have once started to develop the only way to thin is to dig out the crown, but in doing this there is danger of injuring adjacent plants [71]

The Permanent Bed —In preparing the asparagus bed the soil is deeply tilled and thoroughly pulverized before planting This insures a more intimate root-soil contact and promotes vigorous growth Subsoiling heavier soils and plowing under considerable quantities of manure is also a common practice This furnishes a better soil structure and at the same time places stores of available nutrients, upon which asparagus draws heavily, in proximity to the growing roots

Food Storage in Relation to Harvesting —A direct root relation exists in the common practice of permitting the plants to grow 2 full years before the shoots are closely cut Until the plants have had time to manufacture sufficient food for a good crown and root development, they are materially weakened by removing the tops Even on older plants the shoots should not be harvested too late in the season but an abundant growth of tops encouraged The large amount of reserve food required for early spring growth is manufactured by the tops the preceding year before their death and stored in the roots and rhizome The reserve materials stored in the roots in autumn have been shown to be principally sugars The synthesis of sugar in the tops and

its translocation to the roots appear to continue until the tops are killed by frost

> The fertilizing constituents which were stored in the roots over winter appeared to be nearly, if not quite, sufficient for the full development of the succeeding spring crop The production of young stalks drew most heavily on the sugar contained in the roots, but there was no approach to exhaustion of that constituent [108]

Relation to Mulch and Humus —The dead tops, if not removed, afford protection for the roots in winter, holding the snow and preventing sudden fluctuation in soil temperature This is very important in cold climates where the tops are usually supplemented or replaced by a mulch of straw or other material

When the old roots die and decay, they furnish the soil a considerable amount of humus This supplements the supply afforded by the decaying tops Although the plants are widely spaced—usually in rows at least 4 to 6 feet distant and the plants set 1 5 to 2 5 feet apart—yet the extensive root systems fully occupy the soil The amount of humus is so great that the continued use of manure as a source of humus is sometimes apparently not beneficial It is thought that the fleshy roots of asparagus may live and function only 1 or 2 years The constant replacement of older roots by new ones is well known The older ones then decaying

> contribute largely to the humus content of the soil and would seem, therefore, to be a highly important consideration in accounting for the lack of favorable influence of manure on the humus content of asparagus beds [16]

Summary —In conclusion it may be said that the rather thorough studies on the root relations of asparagus have thrown much light upon the activities of the whole plant and have led to a far better understanding of its needs and requirements for successful crop production A knowledge of the root development of the seedlings has permitted more intelligent practice regarding the preparation of the seed bed, methods of planting, spacing, and thinning, preparation of the permanent bed and the time and manner of transplanting A study of the older underground parts has thrown much light upon the care, cultivation, and harvesting of the crop and its needs as regards fertilizers, water, mulching, etc Similar studies on other vegetables will help advance the practice of crop production far beyond the empirical stage.

CHAPTER VII

RHUBARB

Common rhubarb or pieplant (*Rheum rhaponticum*) is a coarse, perennial herb, a new growth arising each year from strong rhizomes. The plant is usually propagated by transplanting portions of the rhizomes and attached roots. It is a cool-season crop, cultivated for its large leafstalks which are available early in the growing season. The plant will withstand the heat of summer, however, and the underground parts are unaffected by severe winter freezing.

Mature Root System.—Four-year-old plants were excavated in early summer near Lincoln, Neb. The large, leafy tops were well developed. About 16 broadly expanded leaves with blades 15 to 23 inches in length and only slightly less in width grew in clumps of average size. A rich, black, silt loam soil of loessoid origin occurred at a depth of 27 inches. It was underlaid with mellow loess subsoil. A sharp line of demarcation separated these two layers of the soil profile. The upper foot of the deeper layer contained numerous pockets or nodules of calcareous material, the remainder to great depths was fine grained and quite free from concretions.

The crowns on selected specimens were about 6 inches in diameter and composed of three to five stems. Each of these short, thick stems was surrounded by dead and partly decayed leaf bases which formed a compact structure extending 5 to 8 inches below the soil surface (Fig. 18). From the base of these stems or rhizomes numerous large roots arose. The largest originated directly beneath the stem cluster and penetrated rather vertically downward, the remainder pursued more horizontal or oblique courses. The largest had a diameter of 3 inches, the others ranged from 1 to 1.5 inches in thickness. In addition a number of smaller roots ranging from 1 to 5 millimeters in diameter arose from the base of the crown and spread horizontally in the surface 12 to 18 inches of soil. These smaller

roots branched and rebranched profusely and carried on considerable absorption in the surface soil

Six or more strong laterals and numerous smaller ones arose from the main root, originating to a great extent in the second foot of soil The course of the major branches was vertically or obliquely downward Many were traced to a depth of 8 feet, the maximum depth exceeded 10 feet

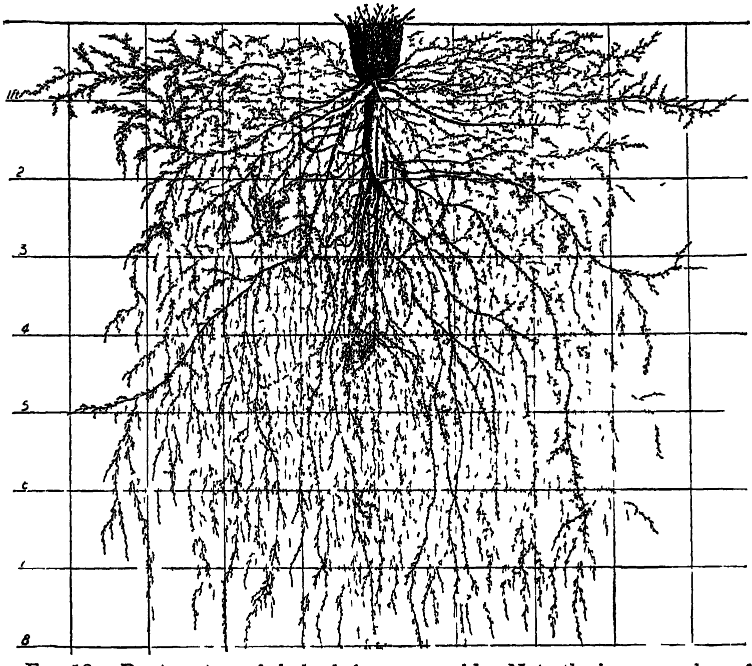


Fig 18 —Root system of rhubarb four years old Note the large number of absorbing roots near the surface of the soil Some of the roots reached depths of more than 10 feet

The thicker portions of the main laterals were nearly always poorly branched with only scattered young rootlets densely covered with root hairs The characteristic gradual tapering of the fleshy roots to fine extremities, as well as the course pursued by the laterals arising from them, may be best understood by a study of the drawing The wealth of fine branchlets and the thorough occupancy of the soil within a radius of 3 to 4 feet of the base of the plant and to a depth of 8 feet or more afforded an excellent absorbing system A maximum lateral spread of 56 inches was ascertained The finer roots rebranched at a rate,

which although somewhat variable, was strikingly uniform at all depths and in the different layers of soil. Usually 4 to 12 branches per inch of root were found. Many of these were simple and only 0.1 to 1 inch long. Many others were 1 to 4 inches or even more in length and furnished with rootlets at the rate of 2 to 8 per inch. The latter were usually short and simple but not infrequently branched. Sometimes, especially on the coarser branches, 2 to 3 inches of root length were quite free from laterals. Young root systems were better supplied with smaller branches than older ones.

The youngest branches were white but the rest of the root had a characteristic reddish or reddish-brown color without and a yellow-colored interior. The roots were brittle and of a rather watery consistency. Even the largest and oldest possessed very little woody tissue. The large branches appeared to increase greatly in diameter with age. The soil beneath the plants was filled to a depth of 8 feet with holes formed by roots now molded away and with many dead roots. These dark-brown to black root remains showed very plainly in the yellowish, loess soil. As the older roots die they are replaced by newer ones. The latter may be readily recognized by the lighter brown or yellow color.

Summary.—The perennial root system of rhubarb is characterized by a thick, fleshy, main root which soon divides into numerous thick branches. These, like the other strong laterals, attenuate gradually and end in very fibrous rootlets. The main roots and their major branches pursue various courses from almost horizontal to nearly vertically downward. Long, slender, much rebranched laterals occur throughout and thoroughly occupy a soil volume with a radius of 3 to 4 feet and extending from the soil surface to a depth of 8 feet.

Relation of Root System to Cultural Practice.—A study of the root system explains why rhubarb flourishes in a deep, rich, mellow, well-drained soil rather than in one that is shallow or underlaid with a hardpan. Since it is an early spring crop, a soil that warms rapidly, such as a sandy loam, is best.

A crop should not be harvested until the roots have become well developed and have a reserve supply of food. The practice of encouraging the growth of a leafy plant but of preventing the growth of the flower stalks is directly concerned with the root activities. The extensive early spring growth of the plant is made at the expense of food stored in the roots during the preced-

ing year Hence, sufficient nutrients should be furnished the plants so that they will make a good growth of foliage after the early leaves are harvested and thus be enabled to manufacture this reserve food supply for the roots In fact, there is usually a direct correlation between a good yield of rhubarb during any year and the growth of the leaves the preceding one If the coarse flower stalks, often 4 to 6 feet tall, are permitted to grow they utilize much of the food that would otherwise be stored in the roots

The large supply of reserve foods in the roots is shown by the practice of forcing rhubarb in cellars In the absence of light, all of the food used by the growing leafstalks comes from the supply already stored in the underground parts before planting them in the forcing bed The fleshy roots are placed in a shallow layer of moist soil which is provided chiefly for the purpose of supplying water to the plant In fact root growth is usually very slight

The common practice of spacing the plants 3 to 4 feet apart in rows 4 to 5 feet distant affords sufficient room for root development, although even at this distance there is considerable overlapping in absorbing territory Where there is a single row, as in most home gardens, closer spacing is permissible

After 4 or 5 years the plants often appear to be "running down" This is thought to be caused by too great a root growth Growers cut away a part of the roots by plowing closely to the plants in the fall or by spading around the clumps Thus, the overcrowded mass of roots is reduced and new growth of roots stimulated This should be done only every 4 or 5 years when the plants seem to require it [24]

The transpiring surface is very large and the roots must absorb and transport to the leaves large quantities of water Hence, thorough cultivation to keep out competing weeds and to maintain a soil mulch is necessary for the best development Because of the proximity of many roots to the soil surface, cultivation should never be deep Mulching the plants with a heavy application of barnyard manure in the fall of the year protects the roots during the winter and also affects them favorably by enriching the soil Soils do not freeze so deeply when covered with a mulch, and root activity may be resumed earlier the following spring, especially if a part of the mulch is removed Rhubarb roots are well fitted for extensive absorption and require a rich soil,

CHAPTER VIII

BEET

The garden beet (*Beta vulgaris*) although a biennial is grown as an annual It is one of the most important of the root crops Beets are hardy and easily grown and are found not only in a large percentage of market gardens but also in nearly all home gardens During the first season of growth it accumulates a large amount of food in the fleshy taproot If the beet is grown a second year, most of the surplus food is used in the production of aerial shoots These are much branched and leafy and reach a height of 2 to 4 feet The "beet" itself is largely the fleshy upper portion of a long taproot The upper part or crown is a very much shortened, fleshy stem, upon the apex of which the leaves are borne The root proper may be distinguished from the stem or crown by the two opposite, longitudinal rows of secondary roots (Fig 21)

Beet seeds of the Edmand's Blood Turnip variety were sown Apr 24 in drill rows 18 inches distant Later the seedlings were thinned until they were 5 inches apart

Early Development—The early root development of the beet is rather rapid Under very favorable conditions for growth, laterals appear on the upper portion of the long taproot only 7 days after the seed is planted

The first field examination was made June 4 when the plants were 6 weeks old The tops were 5 inches tall and each plant had 6 to 8 half-grown leaves about 3 inches long and 2 5 inches wide The total transpiring surface (two sides of the leaves) averaged 1 square foot

The underground parts were characterized by strong taproots which reached depths of 2 5 feet The upper portion of the root had already begun to thicken but below 4 inches it was only 1 to 2 millimeters in diameter (Fig 19) Although slightly kinked and curved, the general course was vertically downward Rapid growth was indicated by the long, unbranched root ends Usually more than 100 branches arose in the surface foot of soil They

spread rather horizontally on all sides of the plant The smaller ones were only 1 inch or less in length and unbranched The longer ones extended away from the taproot for a distance of a foot or more and were well clothed with short, unbranched laterals In the second foot the laterals were almost as abundant but only rarely over 0 3 inch in length

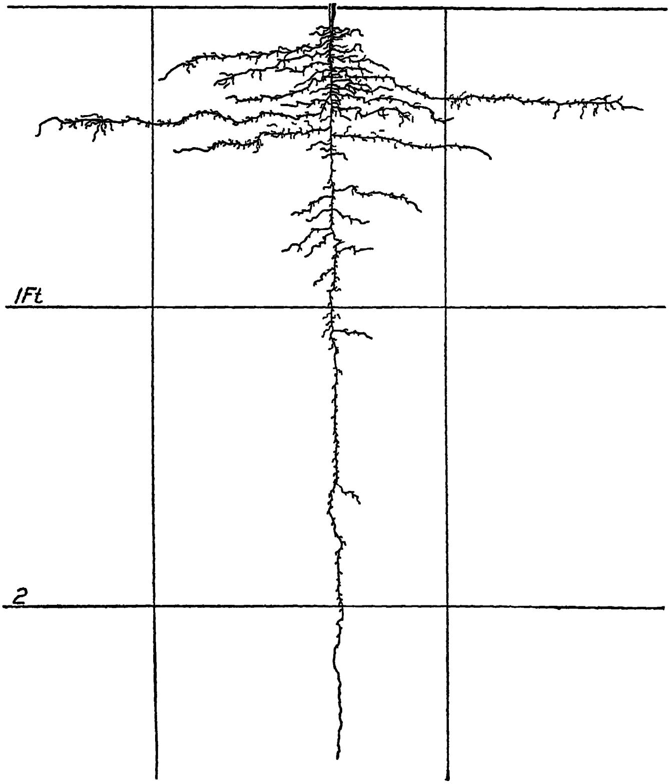


FIG 19 —A garden beet 6 weeks after the seed was planted

Midsummer Growth—A second examination, June 30, revealed marked development The tops were nearly a foot in average height and each possessed about 16 large leaves The area presented for photosynthesis and transpiration was very large since the leaf blades were approximately 8 inches long and 5 to 6 inches wide It had increased to 4 8 square feet

To supply water and soil nutrients for the rapidly growing tops, the plants had developed a remarkably extensive root system

The fleshy taproots were now 1.7 inches in greatest diameter but tapered rapidly under the enlarged surface portion so that they were only 3 to 4 millimeters in diameter at a depth of 18 inches. Beyond this depth the taproots, now only 1 millimeter thick, continued their somewhat tortuous but usually vertical course, reaching depths of 60 to 65 inches in the compact subsoil. The taproot was profusely branched, except near the tip, throughout its entire course. The roots originated in two rows on opposite sides of the taproot which is also characteristic of sugar beets.[68] The vigorous growth of the plants was shown by the long, unbranched ends of the taproot and their larger branches. Often 8 to 11 inches of the root ends were entirely unbranched.

From the lower one-third to one-half of the "beet" many, fine, unbranched rootlets arose. These were only 1 to 2.5 inches in length. Within the first foot of soil the taproot gave rise to from 100 to 125 branches. Many of these (approximately one-third) were only 0.5 to 3 inches in length and entirely unbranched. They were very delicate and almost thread-like. The other branches were larger in diameter and varied in length from 4 inches to 3 feet. A few had a horizontal spread of 4.5 feet. Like the smaller laterals they nearly all took a horizontal or slightly downward course (Fig. 20). They were branched somewhat irregularly but often at the rate of two to eight laterals per inch. These small branches varied between 0.2 and 1.5 inches in length. Many were furnished with short sublaterals. Thus the surface foot of soil was already well ramified with the roots of this crop.

In the second, third, and even in the fourth foot, branching was scarcely less pronounced. The fine laterals were shorter, however, and the longer ones had not had time to pursue their horizontal course for a distance greater than 2 feet from the taproot. Although the secondary branches were shorter, the tertiary ones were practically absent except in the second foot. The number of branches still ranged between two and eight per inch. In the upper portion of the third foot the soil structure was very compact. Owing perhaps to the hard soil, branching of the laterals was noticeably less than on the roots above or below this stratum. The tendency of the roots in the fourth foot to spread only a few inches horizontally and then turn downward was very characteristic. Like the taproots, the long unbranched root ends indicated rapid growth. On the younger, rapidly growing roots laterals were very short.

A somewhat cone-shaped volume of soil, with its apex at about the 5-foot level and its base extending 2 feet or more on all sides of the plant, was being drawn upon to furnish water and nutrients

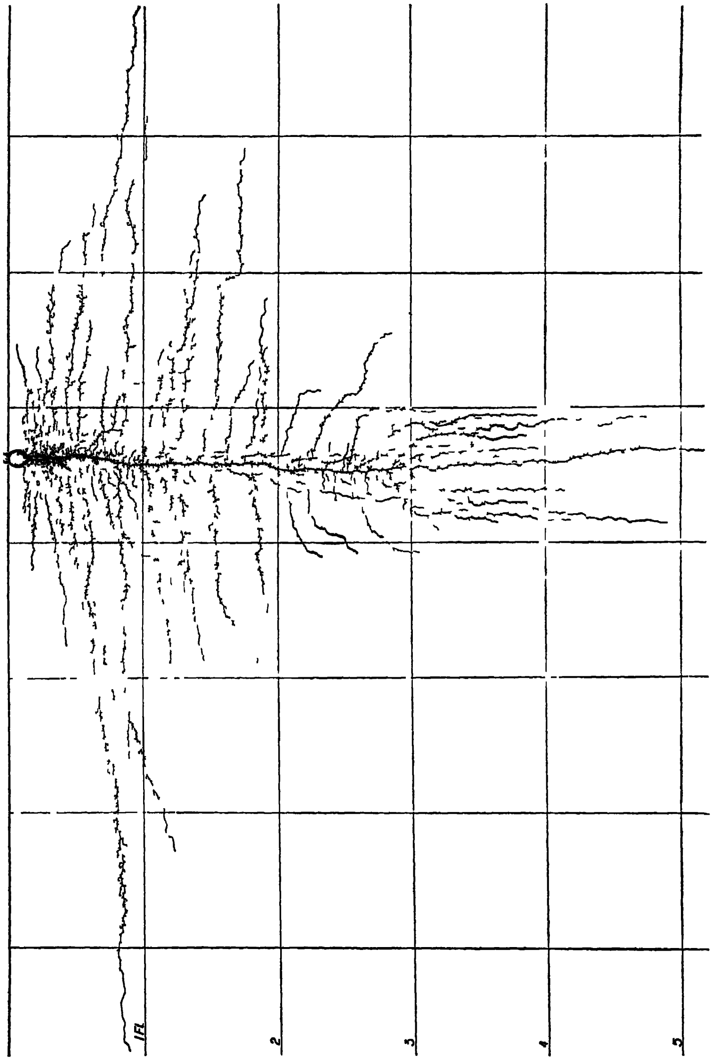


FIG. 20 — A beet about 10 weeks old

for each rapidly developing plant This volume included about 21 cubic feet of soil and subsoil The excavation, examination, and comparison of such an extensive root system were somewhat

easier than usual because of the fact that all except the smallest roots were fairly tough All but the youngest were characterized by the presence of anthocyanin in such abundance as to give them the characteristic dark-pink or reddish color of the "beet" proper

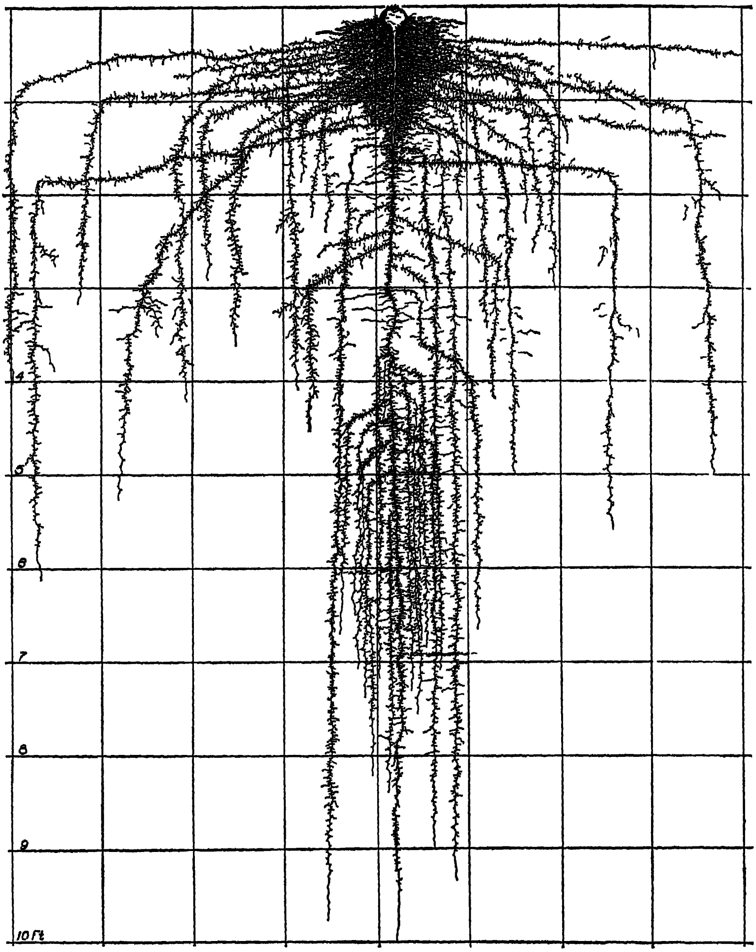


FIG 21 —Root system of the garden beet on Aug 12, about 3 5 months after planting the seed The taproot had elongated at an average rate of over 1 inch per day Note the extensive absorbing area deep in the soil

Maturing Plants—At the final examination, Aug 12, 6 weeks later, the plants had an average height of 11 inches although some were 5 inches taller Plants of average size possessed 24 large

leaves, about one-third of which were dead and 4 to 6 of the younger ones were only partially developed The 10 to 12 fully grown leaves had approximately 60 square inches each of photosynthetic area The "beets" were now 3 5 to 4 inches in diameter

The strong taproots had grown vertically downward, many to the 10-foot level, some reached a maximum depth of 11 feet Large numbers of the formerly horizontal branches in the 2 feet of surface soil had extended laterally for distances of 2 to 4 feet, and then, turning rather abruptly downward, penetrated to depths of 4 to 6 feet (Fig 21) Moreover, a remarkable development of the deeper portion of the root system had occurred Here, the downward-growing tendency of the laterals, already shown late in June, was clearly evident These vertical branches, paralleling the course of the taproot, thoroughly filled the deeper soil, some reaching depths nearly or quite as great as the taproot

Approximately on the lower half of the "beet" short roots occurred in great profusion Here, as in the sugar beet, they are confined to two broad rows on opposite sides of the root As many as 150 roots were counted on a single individual These roots seldom exceeded 8 inches in length and usually most of them were shorter Some were unbranched but others were so profusely branched as to form a dense network of rootlets in the surface soil The abundant branching of the taproots may be seen in Table 12 which illustrates a typical case

TABLE 12—NUMBER OF LATERALS ARISING FROM 1 INCH OF THE TAPROOT AT VARIOUS DEPTHS

Depth, inches	Number of roots less than 1 millimeter in diameter	Number of roots greater than 1 millimeter in diameter	Depth, inches	Number of roots less than 1 millimeter in diameter	Number of roots greater than 1 millimeter in diameter
5	29	4	13	17	2
6	26	5	14	20	1
7	14	4	15 to 20	10 to 15	2
8	12	1	20 to 25	6 to 10	0
9	20	2	25 to 30	6 to 8	1
10	19	3	30 to 35	2 to 6	1
11	25	2	35 to 40	2 to 7	3
12	16	1	40 to 45	3 to 8	3

Many of the smaller branches were hairlike, only 1 inch or less in length, and often free from branchlets The larger laterals were frequently 1 5 to 2 5 millimeters thick throughout much of their course but all tapered to ½ millimeter or less in diameter several inches from their ends The rate of branching was quite variable, ranging from 5 to 10 branches per inch The branchlets were usually 0 1 to 4 inches in length and often quite well furnished with laterals The course of the laterals may be best seen in the drawing In the drier and more compact soil layer at a depth of 36 to 45 inches, branching was poorer and few of the roots were over 2 to 4 inches long But at greater depths from 7 to 10 branches (maximum, 17) normally arose from each inch of the taproot Some were of large size, ran obliquely, and then turned downward and penetrated deeply They were clothed with sublaterals, 0 5 to 2 inches long, in numbers similar to that of the taproot These were poorly rebranched A working level of 7 feet was found although numerous roots penetrated more deeply

The entire root system had the characteristic red or pinkish color except the root ends which were bright and shiny white Even these could be immediately identified by the taste as belonging to the beet Earthworm burrows frequently occurred and seemed most abundant in the deeper soil Upon entering them the roots branched much more profusely, the branches running parallel to the large laterals in the burrows This resulted in dense masses of roots of rope-like structure Some of these branches were also found running horizontally 10 to 12 inches at depths of 7 feet Although some of the cobwebby mats of roots in the drier, upper soil layers had shriveled and died, examination of the bright, turgid, unbranched root ends clearly showed that the roots were still growing

Root Development of Seed Beets.—Beets of the same variety were also grown in Oklahoma They were left in the soil unprotected during the winter Only about one-fourth of the plants survived so that they were spaced 1 5 to 2 feet apart in the rows which were 3 5 feet distant The roots of these surviving plants were dead Renewed growth of tops began about Mar 1 Three weeks later 70 to 260 unbranched roots had developed from two rows on opposite sides of the fleshy, somewhat shriveled "beet" These were mostly horizontal or ran obliquely and only slightly downward They were 0 1 to 6 inches long

By Apr. 18 the plant had a crown of leaves 6 to 9 inches high. Aside from a multitude of fine, hairlike rootlets, about 40 were 1 to 2 millimeters in diameter. These extended 6 to 18 inches on all sides of the plant (maximum spread 23 inches), some penetrated obliquely and reached a depth of 22 inches. Many ended in the 14- to 18-inch soil level. The older parts of the larger roots were furnished with laterals 3 to 4 inches long at the rate of four to six per inch. Many of the smaller roots were also branched, so that quite a network of rootlets filled the soil. These new roots are necessary to supply the demands for water made by the new shoots. They also absorb food materials from the soil which supplement the supply accumulated the preceding year and which thus promote a good growth of tops and an abundant yield of seed.

The plants made a vigorous growth during May and by the end of the month were about 3 feet tall and had five to nine well-branched, leafy stems. In fact they had almost attained their maximum development. The flowering period was nearly passed and fruits had begun to mature.

The root system was very different from that of the first season. About 50 long roots, varying in diameter from 0.5 to 2 millimeters, arose from the lower portion of the "beet" and from the 2 to 3 inches of the attenuated taproot which survived the winter. None of these roots had major branches but were cord-like in character, maintaining their original diameter almost throughout their course. Many of them grew rather parallel to the soil surface at depths of 3 to 12 inches, some reaching a distance of 3 feet from the base of the plant. Others penetrated outward and obliquely downward to distances of 12 to 24 inches or more and ended in the second foot of mellow, moist, sandy soil. Still others pursued a more vertically downward course. These extended deepest, the longest to the 35- to 41-inch soil level. The paths of some of the roots were quite tortuous. The root distribution and the degree of branching are shown in Fig. 22. The larger roots were rather poorly branched on their older portions near the plant (two to eight rootlets per inch). This part of the soil, however, was thoroughly ramified by finer, well-branched rootlets. But throughout most of the course of the roots, except near their tips, branches, usually 1 to 4 inches long but mostly unbranched, occurred at the rate of 16 to 20 per inch

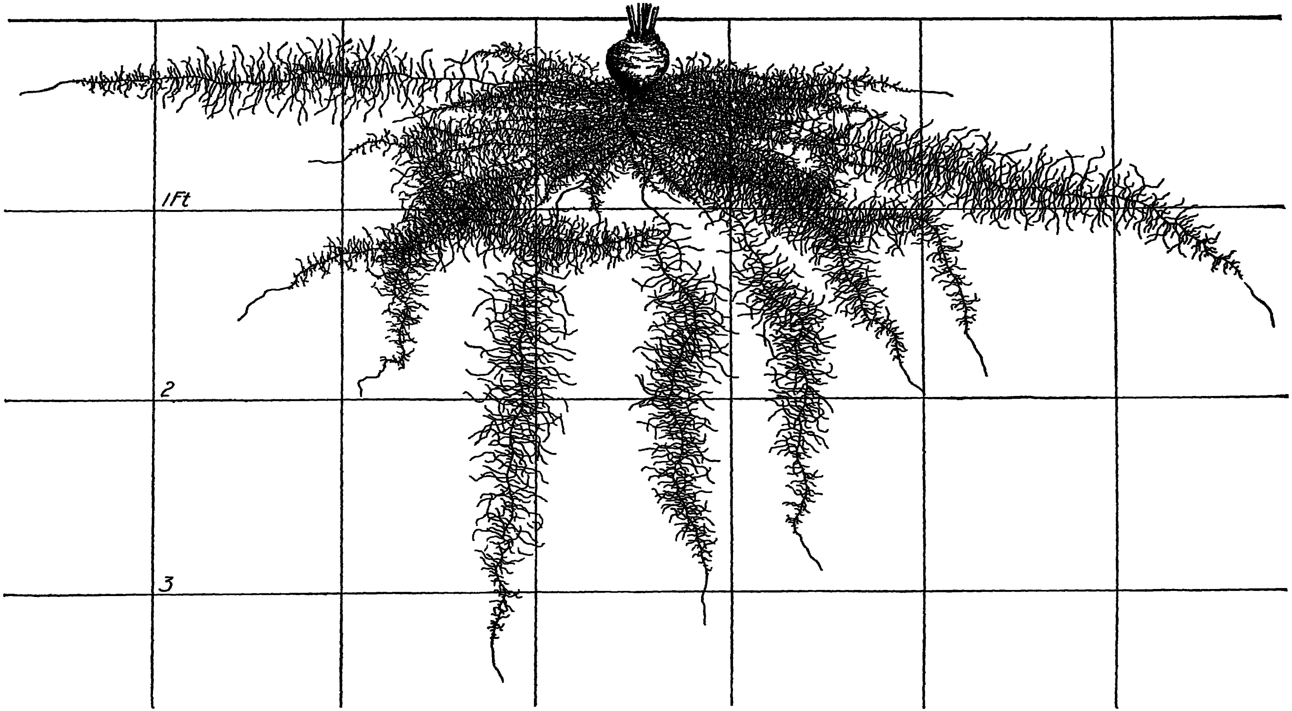


Fig 22 —A portion of the root system of a ' seed beet'' reset in the spring following the first season of growth The old roots had died and all of the fibrous roots grew during the second season

Thus the new root system was not only widely spreading but well furnished with efficient absorbing rootlets.

This root development is similar to that of "mother sugar beets" used for production of seed. In experiments with these it was found that the lower temperatures of early spring or late fall gave a more profuse and more extensive root development than when the beets were set out during warmer weather. This temperature relation was clearly marked.[115]

It is of interest to note that although the roots of the beets were entirely winterkilled, those of the carrot were only partially injured (p. 211), and the roots of the parsnip lived through the winter unharmed (p. 225).

Summary.—The beet has a very pronounced taproot which grows at an average rate of over 1 inch per day during a period of 3.5 months. By the last of June it is 5 feet long and in August extends to the 10-foot level. Two types of branch roots occur in the first 2 feet of soil. The first is exceedingly numerous, short, and repeatedly rebranched. On mature plants they fill the soil in a cone-shaped volume about 16 inches wide near the surface (where they grow out in rows on two sides of the "beet") to its apex at a depth of 2 feet. This portion of the root system develops rather late. Strong branches, intermingled with these shorter roots, also extend horizontally, or only slightly obliquely, some to a distance of 4 feet. Turning vertically downward they then reach depths of 3 to 6 feet. Below 2 feet branches from the taproot grow out more obliquely and turn downward in such a manner that the lateral spread scarcely exceeds 1 foot. They form, with the taproot, an efficient absorbing system in the deeper soil (2 to 8 feet). All of the main roots are profusely branched but with short laterals. Hence, although the root system is very extensive, the soil volume delimited by it is not fully occupied.

The root system of a "seed beet" consists of 40 to 60 fibrous or cord-like roots running horizontally, obliquely, or rather vertically downward. These are new roots which arise from the lower portion of the "beet" and the short remnant of the attenuated part of the original taproot. All are well clothed with unbranched laterals. They thoroughly ramify a hemispherical soil volume having a radius of about 3 feet.

Other Investigations on Beets.—It has been observed in Russia that during the first 3 weeks after planting the root devel-

opment is weak. It later becomes accelerated to a point where the taproots grow 1 2 inches per day and the lateral branches elongate at one-half this rate A root depth of nearly 5 feet and a horizontal spread of nearly 22 inches were attained [123]

An examination of the Extra Long Dark Blood beet at Geneva, N Y., showed that the main root was smooth and symmetrical to a depth of 8 inches Below this it divided into several branches, which were quite thick at first, but rapidly tapered to only a few millimeters in diameter and then to thread-like proportions

> One of the longer ones extended 2 feet downward, while horizontal branches, which were mostly shallow in the soil, extended a distance of 2 5 feet The small fibrous roots seen on the surface of beet roots after they are pulled seem to have very little office, as they penetrate the soil scarcely ½ inch The feeding roots chiefly proceed from the taproot, below the thickened portion Fibrous roots from the branches often extend upward apparently to the surface of the ground The root system of the Eclipse beet, which is a turnip-rooted variety, growing largely above ground, is precisely similar in kind but slightly less extensive We traced the roots downward about 22 inches, and horizontally a distance of 2 feet [43]

There has been observed at this station an early variety of beet and also of radish which appeared to root shallower than later ones, although no such differences were found in lettuce and pea [44]

The rooting habits of Crosby Egyptian beet, an early variety, was also studied at Ithaca, N Y They were grown in a fertile gravelly sandy loam soil underlain at a depth of 8 to 12 inches with gravelly sandy loam which became sandier at increasing depths On plants 12 inches tall and with the fleshy taproot 0 5 to 1 inch in diameter, very few roots had penetrated to a greater depth than 6 inches, although the taproot reached a depth of 15 inches. The space between the 18-inch rows was fairly well filled with roots to the depth of 4 inches When the plants were nearly fully grown and the beets 2 5 to 3 5 inches in diameter the taproot extended to a depth of 2 feet, and some branches from this to 30 inches Small branch roots developed from the taproot throughout its length, some of which were 18 inches long Near the surface a large number of roots ran almost horizontally and extended from one row to another, there being nearly as many in the centers as near the rows The lateral roots were small and of nearly the same size throughout their length and had many small branch roots The greatest development of roots was found in

the surface 3 or 4 inches of soil where they extended from one row to another, there being nearly as many in the centers as near the rows, and many were so near the surface that any kind of cultivation would result in some destruction [159a]

Root Habit Compared with the Sugar Beet.—The sugar beet is one of the forms of the complex species, *Beta vulgaris*, quite similar to the garden beet in root habit. Like the garden beet it develops a strong, deep taproot, a surface root system of profuse, much-branched, widely spreading laterals, and a more vertically penetrating but extensive system of branches which ramify the deeper soil. Extensive experiments in fine sandy loam soil at Greeley, Colo., have shown that the root system is very susceptible to modifications brought about in the soil environment by variations in the water content, fertility, etc [68] It seems probable that the garden beet would respond in a similar manner. For example, the Kleinwanzelebener variety of sugar beet in dry soil had a smaller taproot which pursued a more tortuous course, did not penetrate so deeply, and was branched more nearly to the tip than similar plants in moist soil. The larger, deeper-seated branches turned downward rather abruptly, reaching depths of 3 to 4 feet. Branching was more profuse throughout. Development of the surface absorbing system may be greatly delayed, although it branches more profusely and may extend even more widely when the soil becomes moist. The root systems of mature plants grown under irrigation and other very favorable conditions were less extensive than that of the garden beet. Depths of 5 to 6 feet were attained and the lateral spread seldom exceeded 18 inches.

Studies in Germany show that not only the sugar beet but also mangels and certain other closely related, fleshy rooted forms are very similar in habit to the garden beet just described [83]

Root Habits in Relation to Cultural Practice.—The very deeply penetrating root system of the beet explains why, like other root crops, it thrives best in a deep, friable, well-drained, but moist soil. A consideration of the very fleshy portion of the taproot makes clear why a deep, mellow, easily moved soil is essential for a proper development of the beet. In heavy soil the beets are likely to be unsymmetrical in form. Hence, in preparing the seed bed the soil should be well pulverized, loose, and smooth, but not so loose that it quickly dries. A heavy soil is less satisfactory. It becomes hard and cracks or if kept wet it

puddles, conditions very unfavorable for the germination of seed. The actual depth of cultivation varies, of course, with the nature of the soil and the previous depth of cultivation. Poor soil preparation is likely to result in an inferior stand of plants, regardless of the high quality of the seed sown. No amount of later cultivation will compensate for carelessness in the preparation of a seed bed. Early and frequent tillage not only keeps down weeds but also prevents the formation of a soil crust and the subsequent difficulty in the emergence of the shoot. It promotes good aeration.

Since each fruit of the beet contains more than one seed, the plants come up in clumps and must be thinned. The time and manner of thinning is closely related to root injury. Late thinning greatly disturbs the roots of even the more vigorous plants left to mature. The widely spreading and deeply penetrating root systems are undoubtedly an important factor in competition and the resultant reduction of yield where the crop is too thickly grown.

A study of the root system shows that the beet used in this investigation did not depend largely on the surface 4 to 6 inches of the soil for its water and nutrient supplies. A comparison of the soil-moisture data in Table 2 shows that cabbage (as is indicated by its more superficial root system, Fig. 29) reduced the water content in the surface foot of the soil to a much greater degree than did the beet. At greater depths, however, the soil in the beet plats was usually drier. It would seem that cultivation of the soil for the purpose of retaining moisture should have some advantage over removing the weeds by scraping.[152,158] At Ithaca, N. Y., an average gain in yield of 4.25 per cent as a result of a soil mulch has been reported for an early beet which rooted extensively in the surface soil.[159a] The large tops, of course, would more or less thoroughly shade the soil and thus retard surface evaporation. Only a few inches of surface soil, except that close to the plant, were, under the conditions of growth described, unoccupied by roots. The lack of superficial roots, except those very close to the plant, permits of deeper cultivation without root injury than is possible in the case of many garden crops. Some varieties, however, and perhaps all varieties under certain conditions, fill the surface soil also with a network of roots. Likewise, a practice of getting manure and other fertilizer worked well into the deeper soil would seem justifiable. This would not

only place the manure more easily within the reach of the roots but also at the same time improve the physical condition of the soil

The close spacing of beets, usually 4 to 8 inches apart in drills or rows 1 to 2 5 feet distant, results in much overlapping of absorbing territory and a thorough occupancy of every cubic inch of soil It is not surprising that garden soils must be kept very rich where, as is often the case, beets are grown as companion or succession crops

CHAPTER IX

SWISS CHARD

Chard (*Beta vulgaris cicla*) is a biennial plant with a strong taproot and large leaves clustered on a short stem near the soil surface. It is really a foliage beet and is grown as an annual. Cultivation has changed its habit of growth so that leaves instead of roots are best developed. The leaves, for which it is grown, have large, fleshy leafstalks and broad, crisp blades. It withstands the heat of summer better than most crops grown for greens. The leaves are prepared like those of spinach by boiling and are canned for winter use. The petioles and midribs are frequently cooked and served like asparagus.

Seed was sown at Norman, Okla., Apr. 19, in rows 3.5 feet apart so as to permit cultivation with a horse-drawn harrow. The seed readily germinated in the warm, moist soil and by May 14 thrifty seedlings, 3 to 5 inches high, were abundant. They were thinned to 8 inches apart in the row.

Early Development.—The root system at this time consisted of a taproot which branched profusely in the first 6 inches of soil, giving rise to both large and small laterals at the rate of about eight per inch. These extended outward and usually slightly downward, although a few ran rather sharply obliquely downward. The greatest lateral spread was 14 inches and a depth of 19 inches was attained (Fig. 23). The laterals and the taproot below 6 inches bore unbranched rootlets for the most part, only a few of the stronger ones were rebranched. Secondary laterals near the taproot were about 2 inches long but rapidly decreased in length on the younger portions of the main branches.

Half-grown Plants.—The seedlings had developed into vigorous, rapidly growing plants by June 7. They were 1 foot tall and each had 8 to 10 leaves. The larger leaf blades were 4 inches wide.

The strong taproot (15 millimeters thick near the soil surface) and some of its larger branches had become somewhat fleshy. The gradually tapering taproot penetrated, with small irregu-

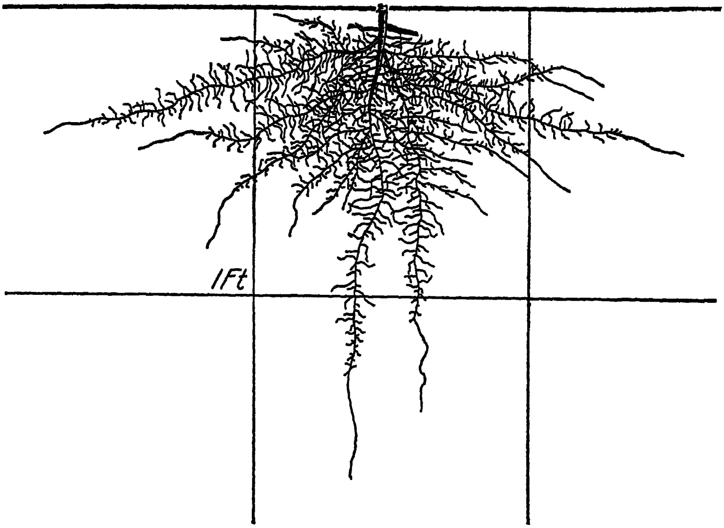


FIG 23—Root system of Swiss chard 25 days old

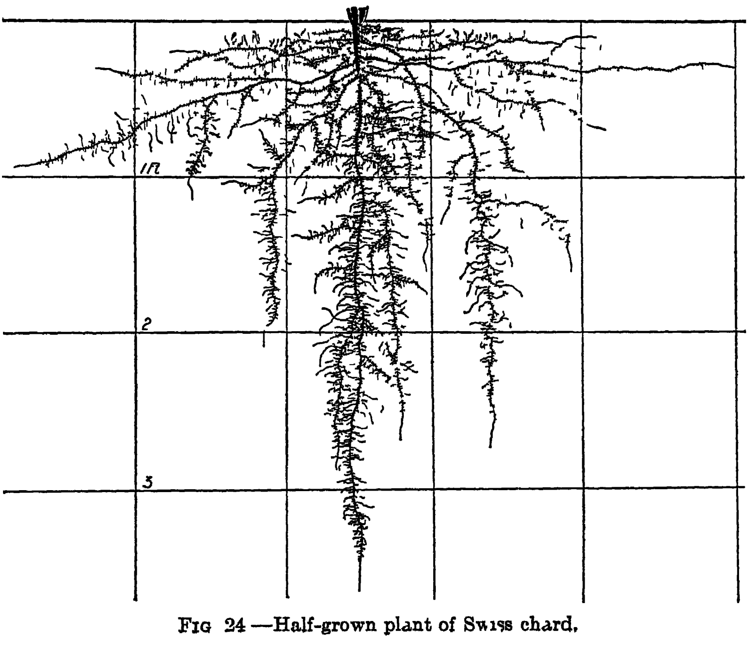


FIG 24—Half-grown plant of Swiss chard.

larities, directly downward to a depth of 45 inches. As before, the largest branches were on the first 6 inches of the taproot. Many of these had a horizontal course throughout and branched very profusely in the moist, mellow, surface soil. A maximum spread of 2.5 feet was attained. Other laterals turned downward within 1 foot from their origin and pursued a generally vertical course parallel to that of the taproot to depths of 2 to nearly 3 feet (Fig. 24). The portion of the taproot below 6 inches was very well branched, some of the branches exceeding 1 foot in length. Their direction of growth varied from horizontally outward to vertically downward. The larger roots of the entire plant were well supplied with absorbing laterals at the rate of 6 to 12 per inch. Some of the older of these unbranched rootlets were 4 inches long. On the first few inches of the taproot and on some of its larger branches the absorbing laterals were beginning to die. Otherwise the conical mass of soil, 5 feet broad and 3.5 feet deep, was well filled throughout with an actively absorbing root network. The plants were again thinned, this time to 2 feet apart in the row. This reduced competition and permitted better growth of the individuals.

Midsummer Development.—By July 28 the tall, branching crowns were thickly clothed with a dense foliage. As many as 25 leaves, 1.5 to 2 feet long, were common on individual plants.

The taproots were about 2 inches thick. They had increased greatly not only in extent but also in complexity of branching. With characteristic short turns, one taproot penetrated vertically downward, branching freely, to a depth of 4 feet. Here it divided into two rather equal parts but continued its course to a depth of nearly 7 feet. Most of the taproots and their longest, stronger branches did not extend beyond 6 feet, but one was traced to the 7.5-foot level. Accompanied by strong branches, descending parallel with it, the taproot and its profuse laterals occupied a soil volume which, below the second foot, was about 18 inches in diameter and extended nearly to the 6-foot level (Fig. 25).

The part of the root system in the surface 2 feet had similarly increased. Large, horizontal branches, 10 to 15 millimeters in diameter at their origin, extended widely in the surface foot of soil. Running horizontally at a depth of 4 to 8 inches, they extended to distances of 3 to 4 feet (maximum spread, 53 inches) from the base of the plant. Although the small absorbing laterals in the first 2 to 2.5 feet of their course had mostly withered,

at irregular intervals (often 0 5 to 2 inches or more) they gave rise to larger branches Similar branches, of course, occurred farther out on these roots, intermixed with the simple laterals They grew in all directions, often upward near the soil surface The longest ones, some of which penetrated almost vertically

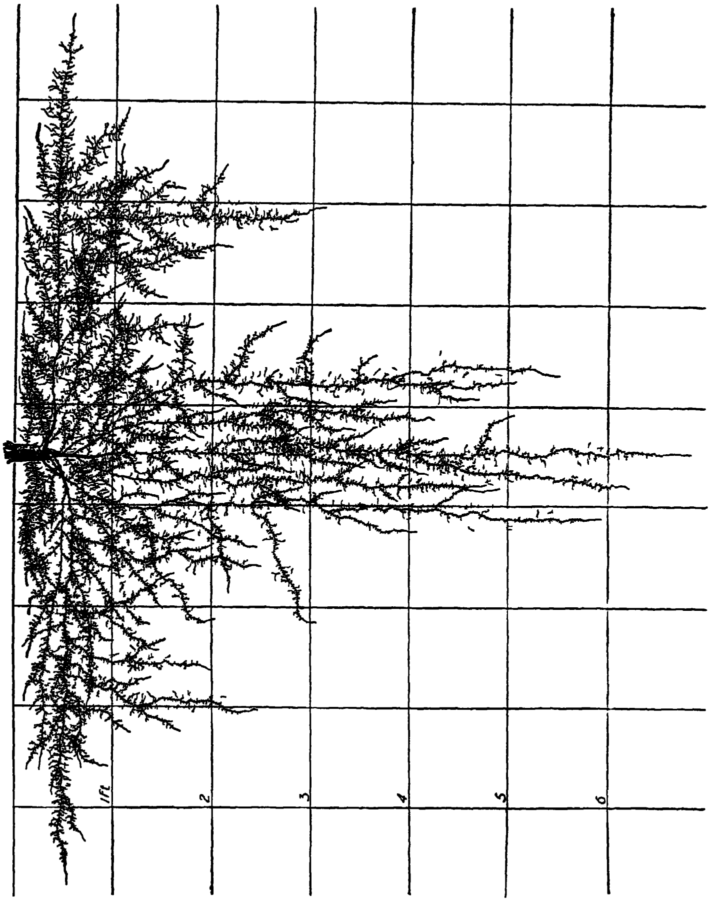


FIG 25 —Midsummer root development of Swiss chard Only one-half of the root system is shown

downward, were 2 to 2 5 feet in extent (Fig 25) These and their major branches provided a network of roots throughout the surface 2 feet of soil upon which small laterals grew at the rate of 12 per inch Thus the root system occupied a large soil volume and was well fitted to draw upon the abundant supplies of water and soil nutrients

Root Development of Seed Plants —The degree to which the old root system of biennial or winter annual vegetable crops deteriorates and to which a new growth of roots occurs is a subject which deserves thorough investigation The following observations are indicative of the behavior of Swiss chard Plants grown during 1925 were left undisturbed in the field at the end of the growing season, and the root behavior was examined during winter and spring No root growth was found until the renewed top growth of spring began about Mar 15 The environmental conditions during the period are given on page 19 At this time very large numbers of new absorbing rootlets were growing from the old taproot and its stronger branches These were from 0 5 to 4 inches long and occurred in clumps on opposite sides of all of the larger roots They were very abundant to a distance of 2 feet outward on the large horizontal roots and extended 18 inches downward on the vertically descending ones Many of the older, finer roots were also showing renewed growth

By June 12 the plants were 4 to 5 feet tall Each had from three to six well-branched stalks 1 to 3 inches in diameter The soil within 2 feet of the plant had been very thoroughly exhausted of its available water The dense growth of roots just described was dead But at distances greater than 2 feet from the taproot, the horizontal roots were well supplied with an abundance of fine laterals which grew from the finer branches of the old root system The root system as a whole was no more extensive in regard to the volume of soil occupied than at the March examination But branching was more profuse near the extremities of both vertical and horizontal roots

Root Development Compared with Beet —Compared to its close relative, the garden beet, the root system lacked the network of fine absorbing laterals originating from the taproot in the surface 12 to 18 inches of soil Neither did the widely spreading main laterals, arising in the surface foot, show the habit of finally turning downward and penetrating deeply Instead they gave rise to many, large, downwardly growing branches, a root habit quite different from that of the beet Moreover, long branches, originating from the taproot in the deep soil, were not found, although they are very characteristic in the garden beet In these and other minor respects the root habits are quite different

Summary.—The root system of Swiss chard is characterized by a strong taproot and many strong lateral branches all of which

originate in the first foot of soil It makes a vigorous growth and early in June occupies a conical mass of soil 5 feet in diameter and 3 5 feet deep Mature taproots are 2 inches thick, but taper rapidly, and penetrate to depths of 6 to 7 feet The strong, widely spreading, horizontal branches, with their long and profusely rebranched laterals, thoroughly occupy the soil from near its surface to a depth of 2 feet and throughout a radius of 3 5 feet from the plant Almost vertically descending laterals, paralleling the course of the taproot, and like it well clothed with branches, ramify a soil volume about 18 inches wide to a depth of 6 feet Thus the root is well fitted for absorption both in the surface and in the deep soil During the second year the plant increases its absorbing surface by a dense growth of rootlets on the older portion of the root system This is further augmented by the renewed growth of many of the finer rootlets already formed on both the surface and deeper portions of the root system

Other Investigations on Swiss Chard—It has been found at Geneva, N Y, that the root system of Swiss chard is decidedly more extensive than that of the garden beet In September, the roots of Beck's Sea Kale chard were traced horizontally to a distance of 3 5 feet At a depth of 2 feet the taproot was still 4 to 5 millimeters thick

> The taproot and larger branches were thick and fleshy near the surface, the former regularly tapering as it extended downward, giving rise to branches on all sides Some of the latter were ¾ inch in diameter, the larger ones starting about 4 inches below the surface Fibrous roots were numerous in the upper layers of the soil The chard is a plant of the beet family in which the foliage instead of the root has been developed through selection It is interesting to observe that with a decided increase of foliage over the common garden beet, we have a corresponding extension of roots [43]

Root Development in Relation to Cultural Practice.—The vigorous development of the very extensive root system and perhaps its ability to adapt itself, like the sugar beet, to different environments, may account for the fact that chard is not as exacting in soil requirements as most other vegetable crops It is a hardy, vigorous plant, and with a little protection will live through the winter Any good garden soil is satisfactory for this easily grown plant

It would seem that in growing chard, as well as most deeply rooting plants, that a deeply rooted crop like clover preceding it would be most favorable as a green-manure crop to supply humus The roots of the clovers extend deeply and have a very beneficial effect upon the soils to a greater depth than most green-manure crops The effects of roots of legumes upon their death and decay in loosening and aerating the deeper soil are very great After clover and alfalfa have been grown in it, the soil is quite filled with root channels which greatly modify its structure and promote aeration The decaying roots add considerable amounts of manure In the case of a good stand of 2-year-old red clover, for example, 6,580 pounds of vegetable matter—over 3 tons per acre—were left as roots in the soil Chemical analyses showed that this included 180 pounds of nitrogen, 71 pounds of phosphoric acid, and 77 pounds of potash [3]

Effect on Soil Structure—Extensive root systems like those of chard and beet must exert a pronounced effect upon soil structure It seems that with the usual spacing of these plants, the soil would be thoroughly ramified with roots Investigations on the influence of plant roots on the structure of the soil show that in loose soils a very small percentage of the soil spaces is filled by the stronger roots so that no essential decrease in the original mellowness from this source occurs But in compact soils roots may to a certain degree improve the structure and thus increase production In compact stiff soil without granular structure, the loosening process is aided, to the benefit of plant growth, by the mechanical action of roots and by a strong modification of the moisture conditions The beneficial combination of self-loosening and root action explains the frequent permanent improvement of the soil structure under the continued influence of roots, as in grasslands,[172] and also the prevention of the permanent puddling of the soil by rain It has been found that a marked surface spreading of roots has a beneficial influence upon the penetration and movement of water in the soil Water movement is much more rapid, although lateral percolation and loss of water through evaporation is retarded Where the soil is occupied by plants throughout the year, the effects are most marked.[12]

CHAPTER X

SPINACH

Spinach (*Spinacia oleracea*) is an erect, smooth, annual herb of rapid growth, related to the beet. It is the most important of the potherbs or greens grown in this country. It is a hardy plant, and the foliage for which it is grown develops rapidly. Early in the season numerous large leaves are crowded on the short stem just above the soil surface. In the North it is grown as an early spring and late fall crop but in the south mainly as a winter crop. During the summer the plant produces a flower stalk 2 to 3 feet in height and develops seed.

Seed of the Curled Savoy (variety *inermis*) was planted Apr. 10 in drills 12 inches apart. After the plants were well established, they were thinned to 4 inches distant in the row.

Early Development.—At the initial examination, May 23, the plants had 10 to 12 leaves each. About seven of the largest had blades 2 to 4 inches long and 1.5 to 3 inches wide. The transpiring surface averaged 134 square inches, exclusive of the yellowed cotyledons which were still on the plants.

Spinach is characterized by a strong, vertically and deeply penetrating taproot. The root near the soil surface was already 9 millimeters in diameter. It tapered gradually to a thickness of a millimeter at the 10-inch level and retained this diameter throughout its course. Curves and kinks in the taproot were quite pronounced in the harder, second foot of soil. Below this the roots were straighter to the maximum depth of 32 inches. No laterals arose within ½ inch of the soil surface but in the surface foot from 62 to 80 horizontally spreading roots took their origin. Among these usually about 8 to 10 were of distinctly larger diameter (0.5 to 0.8 millimeter) although there was no clear distinction between long and short roots. The laterals originated in two rows on opposite sides of the taproot. A few ran slightly obliquely downward. The greatest lateral spread was 15 inches. As shown in Fig. 26, the longest branches were in the surface 6 to 8 inches of soil. It was in this older portion of the root

system also that the most branching occurred Secondary laterals were never profuse (only 3 to 7 per inch), rather short (mostly 0 1 to 0 5 inch), and only a few of the longest were rebranched

Below the 8-inch level the main laterals were only about 1 to 3 inches long and in the harder soil of the second foot much shorter The rapidly growing root ends were free from branches

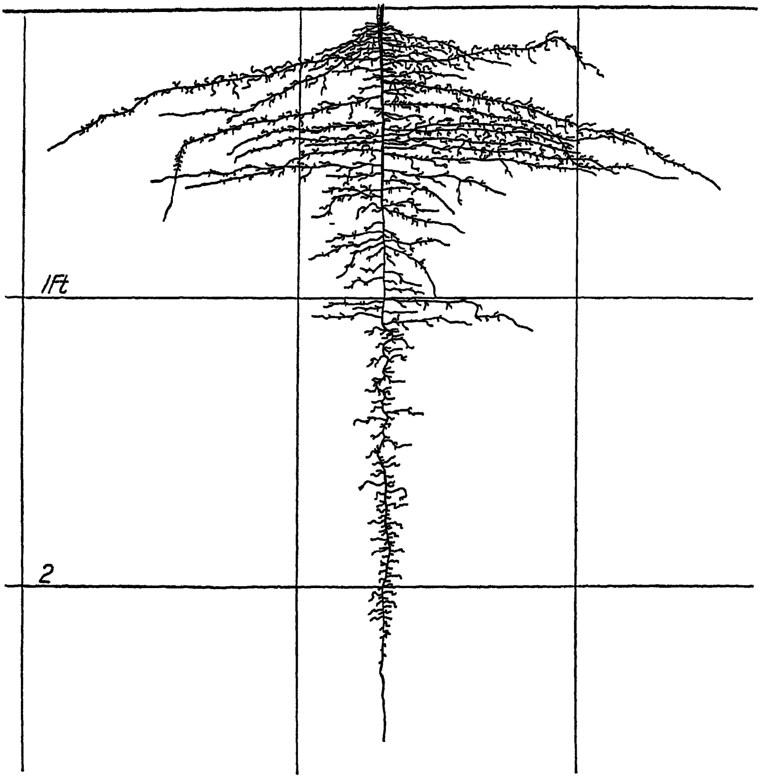


FIG 26 —Six-weeks-old root system of Curled Savoy spinach

Half-grown Plants.—A second examination was made June 17 The tops had a spread of nearly 1 foot and averaged 13 inches in height About 65 leaves were found on plants of average size The larger ones near the base had leaf blades 4 by 5 5 inches Thus the transpiring surface which was now 2 2 square feet, had greatly increased.

The underground parts had grown in a corresponding manner The strong taproot was 15 millimeters in diameter and enlarged throughout the first 6 inches of its course It reached a depth of

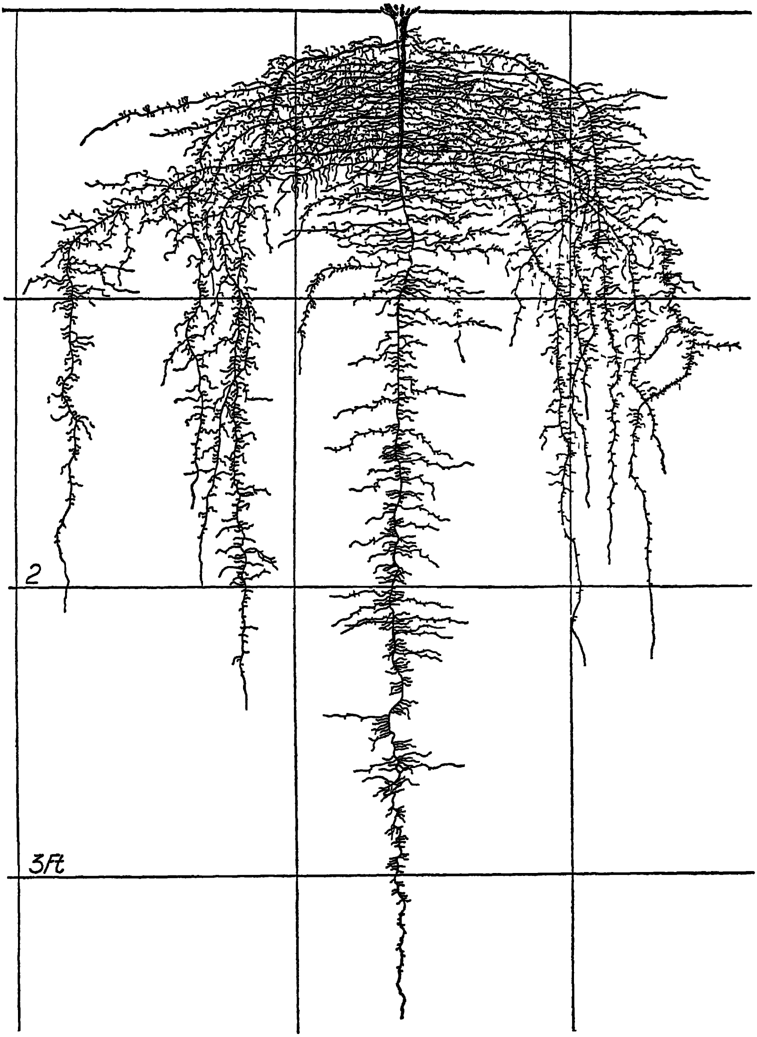


FIG 27—Spinach on June 17, at the age of 10 weeks

3 5 feet It bore abundant laterals to within a short distance of its tip An examination of Fig 27 shows that the absorbing system had been increased in three ways by an elongation of

branches and greater branching in the soil area formerly occupied (*cf* Fig 26), by a downward extension of many of the larger laterals, and by the elongation or development of numerous branches from the taproot below the first foot

Branching in the surface 8 inches of soil was now quite profuse Secondary branches commonly varied from 0 5 to 1 inch in length but occasionally branches 2 to 8 inches long occurred These were clothed with laterals at the same rate as the main branches which was about seven per inch Short branches of the third order frequently occurred in abundance Moreover, there were many more laterals on this portion of the taproot than at the earlier examination

Figure 27 shows that the widely spreading laterals (maximum extent, 14 inches), some of which descended to the 2-foot level or beyond, were also well branched Branches on the taproot below 8 inches were, with few exceptions, quite horizontal but did not spread widely Below 1 5 feet they frequently occurred in groups, sometimes being confined to one side of the root for a short distance Frequently as many as 12 arose from a single inch of taproot The unbranched condition of the younger roots, as well as the absence of laterals from the main root ends, indicated that growth was proceeding rapidly

Mature Plants —A final examination was made July 10 on maturity of the plants They had stems over ½ inch thick and 2 feet high All the basal leaves and many of the stem leaves were dry The plants had blossomed and set fruit

The taproot had a diameter of over 1 inch near the soil surface but tapered gradually to 1 millimeter in thickness at the 15-inch level It reached a depth of 6 feet In the first 6 inches of its course 40 to 46 laterals took their origin Nearly half of these were large ones On the deeper half of the first foot of taproot, however, only 18 to 20 laterals were found and all but one or two of these were relatively small In fact no large branches occurred below the 10-inch soil level But to a depth of 2 feet small branches were found in great profusion—as many as 80 on the second foot of taproot alone These varied in length from 0 5 to 3 inches The longest were rebranched with short rootlets At still greater depths branches arose at the same rate as at the preceding examination, about 8 to 12 per inch These had increased somewhat in length, most of the rootlets still pursued a horizontal course, and sublaterals were more abundant

The widely spreading laterals which originated in the surface 6 inches of soil now reached depths of 3 to 4 feet. Also some of the larger branches originating at greater depths had extended outward and then turned downward so that the soil around the taproot was more thoroughly occupied. Many of the root ends were decayed. Branches on these main laterals 5 to 10 inches in length were not uncommon. The rate of branching was 6 to 18 laterals per inch and the length varied usually from 0.2 to 3 inches. Branchlets of the third order were abundant.

Thus the soil volume delimited at the June examination was much more thoroughly ramified. It has also been extended from a depth of about 2 feet (exclusive of that occupied by the taproot) to about 4 feet. The roots were yellowish in color and rather brittle.

Summary.—Spinach has a pronounced taproot which grows rapidly, penetrates deeply, and gives rise to major branches only in the 6 to 10 inches of surface soil. These spread rather horizontally, usually a foot or less, and then, turning downward, penetrate to depths of 3 to 4 feet. Branching on the first foot of the taproot is very profuse, the finer branches with the laterals from the main roots quite fill the soil volume, the upper surface of which is early blocked out. The taproot, below the first foot, is clothed with relatively short but numerous branches. These add considerably to the absorbing surface in the deeper soil. A depth of 6 feet is attained.

Other Investigations on Spinach.—Very little study has been given to the root habit of spinach. At Geneva, N. Y., the Prickly or Winter variety was examined on July 28.

> The deepest growing root extended downward about 2 feet and the longest horizontal roots reached about 18 inches. The feeding roots seemed chiefly to lie at a depth of about 6 inches, though many fibrous roots rose upward to within 2 inches of the surface. The root was a thickened taproot to the depth of 4 inches, below which it divided into many branches of varying length and thickness.[43]

Allowing for differences in soil structure, etc., it would seem that the method employed of washing away the soil failed in revealing the entire root extent.

Root Development in Relation to Cultural Practice.—The extensive root system, rapid growth, and great transpiring area are clearly correlated with the best soil combination for the growth

of spinach, *viz* one that is rich and well drained but constantly moist Hence, the practice on flat lands of plowing the soil into low, flat beds The extra drainage afforded also keeps the soil from "heaving" and thus tearing the roots of the winter crop The plant did not develop a shallow portion to its root system as do many vegetable crops and it is thus less likely to have its roots disturbed by cultivation The lack of shallow root development may have been due in part, however, to a dry surface soil In more moist soil many roots might pursue a course nearer the soil surface The extensive occupation of the surface 2 to 8 inches of soil suggests not only a thorough preparation of this portion of the substratum in regard to humus content and good tilth but also the most effective depth at which to place the fertilizer The plant must make a quick growth to be crisp and tender and abundant soluble nitrate compounds within reach of the roots promote development of foliage The usual spacing of the plants, about 6 inches apart in rows 8 to 14 inches distant, results in considerable root overlapping and a complete occupancy of the soil Root competition is ameliorated to a great extent, however, by well-prepared, very rich soil in which the moisture is conserved by weed eradication and by the preservation of a surface mulch

CHAPTER XI

CABBAGE

Cabbage (*Brassica oleracea capitata*) is a hardy, biennial plant, although grown as an annual crop It is one of the most important of vegetables It is a cool-weather crop, properly hardened plants being able to resist temperatures much below freezing In the South it makes its growth mainly in the spring or fall Like the other cole crops, cabbage is grown for its vegetative aboveground parts The common cabbage, during the first year of its growth, produces a short stem which terminates in a large bud composed of thick, overlapping, smooth leaves, the whole structure being known as the "head" Different varieties are adaptable to a wide climatic range, and it is grown almost throughout the United States In the North, especially, the early cabbage is usually started under protection and transplanted into the field

COPENHAGEN MARKET CABBAGE

Plants of the Copenhagen Market variety were transplanted into the garden Apr 10 The plants were placed 40 inches apart in rows which were 3 feet distant

Early Development—The first examination was made June 4 The plants were about 5 inches tall and each usually possessed 20 to 25 leaves The larger leaf blades, about 10 in number, averaged 4 5 inches both in length and width, the remainder only 2 5 inches in these dimensions Although the plants were still small, the transpiring area, including both upper and lower leaf surfaces, was already only slightly less than 3 square feet

In all of the several plants examined a main root arose from the base of the enlarged underground part (the taproot having been destroyed in transplanting) and ran in a somewhat tortuous downward course These roots reached maximum depths of 38 inches Most of the laterals ran outward and downward, often at an angle of approximately 45 degrees or more from the perpendicular, to depths of 6 to 8 inches At this depth many

pursued a rather horizontal course in the second 6 inches of soil. They frequently reached a lateral spread of 3 feet on all sides of the plant. A few continued their obliquely downward course, ending 1.5 to 2.5 feet from the main vertical root at depths of 12 to 24 inches (Fig. 28).

Few branches arose in the surface 2 to 3 inches of soil. The main lateral roots, usually 22 to 28 in number, were only fairly well clothed with branches. Sometimes an inch of root had only two to four branches but usually laterals 0.5 to 1.5 inches in length occurred at the rate of 4 to 7 per inch. These were

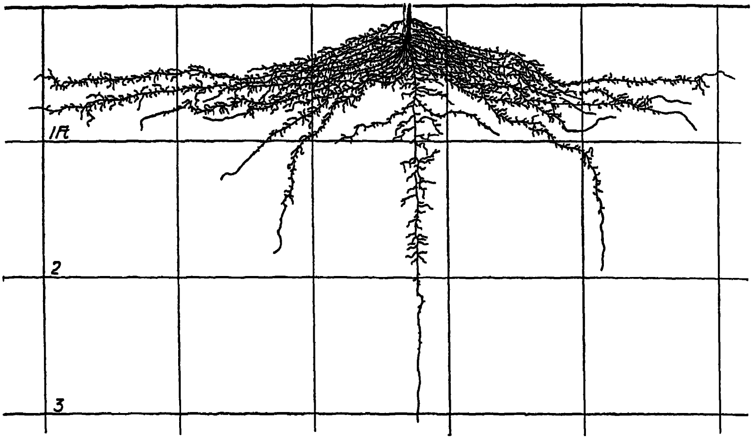


FIG. 28.—Root system of Copenhagen Market cabbage 55 days after transplanting into the field.

unbranched. The upper portion of the main vertical root had a few rebranched laterals 3 to 9 inches long. Below 12 inches they seldom exceeded 3 inches in length and the deepest portion was quite unbranched. Since practically no roots occurred in the surface 6 inches of soil, except near the plant, cultivation at this time would have resulted in a minimum of root injury.

Midsummer Growth.—Twenty days later, June 24, the cabbage was again examined. The plants were 1 foot high and had a total leaf spread of 26 inches. The transpiring area had increased to 19 square feet. The heads were 4 to 5 inches in diameter.

During the 20-day period a remarkable development of the root system had occurred. The main vertical roots now reached depths of 4.5 to nearly 5 feet. The widely extending main lateral roots ran obliquely outward and downward and at a depth

of 12 inches were 2 5 feet horizontally from the base of the plant A maximum lateral spread of 41 inches was attained near the 3-foot level These long roots reached depths of 3 feet or more

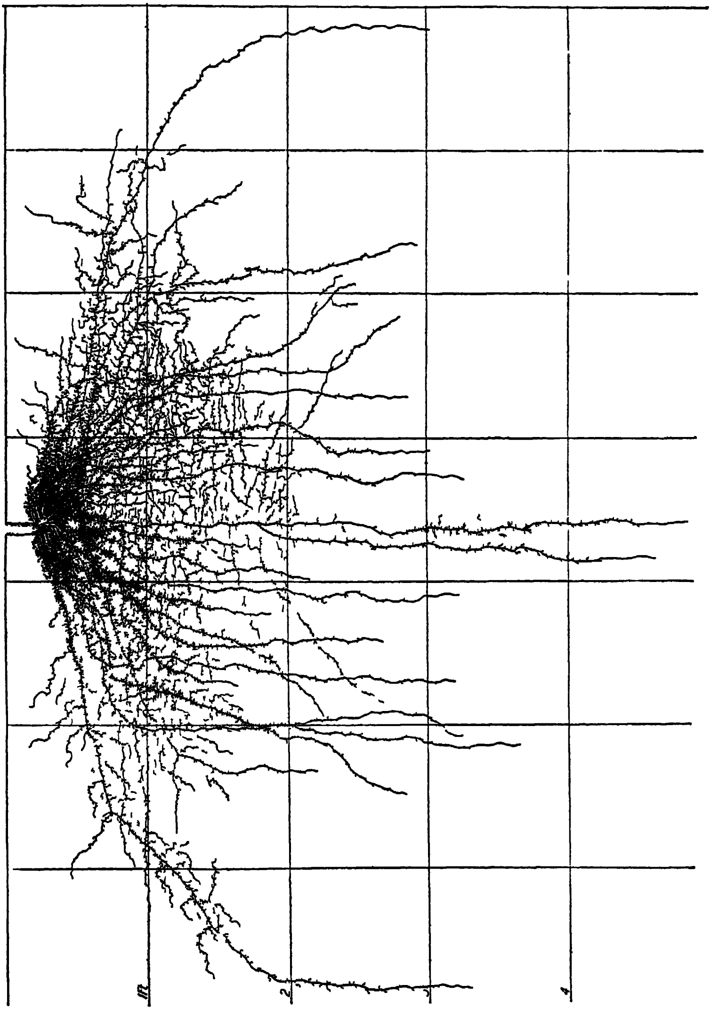


Fig 29 —Cabbage excavated 20 days later than that shown in Fig 28 Note the marked growth during the 3 weeks' interval

Within the soil volume thus delimited many roots arose from the enlarged underground part They pursued such varied courses that the soil was quite filled with them and their branches to a depth of at least 3 feet (Fig 29) Reference to Fig 28 shows that

many of the rather horizontal laterals of the earlier stage had grown downward and that new roots had occupied the soil directly beneath the plant.

Practically no roots arose from the upper part of the enlarged basal portion of the plant (which had a diameter of nearly 1 inch) but from its terminal part it gave rise to 30 to 38 roots. Most of these ranged from 3 to 6 millimeters in diameter, a few were smaller. These long, cord-like roots tapered gradually so that below 18 inches none were more than 1 millimeter in diameter and usually less.

Branching, especially in the first foot of soil, was very profuse. From a large number of counts it was found that the number of branches per inch on the first foot of the laterals varied from 22 to 26 (maximum, 47). Although short and only fairly well rebranched, these rootlets were so very abundant that the soil was thoroughly filled with them. Frequently, they originated in groups. On the second foot of the laterals, the branches were longer (0.2 to 1.5, rarely 2.5 inches) and, although still very abundant, fewer (*e.g.*, 5 to 7) per inch. But on some roots as many as 22 rootlets per inch occurred. All were more or less thread-like and usually 0.1 to 0.5 millimeter in diameter. They were poorly rebranched. From the widely spreading, almost horizontal roots, laterals, 3 to 12 inches in length, frequently arose. These extended in various directions, some almost directly upward. A few ended within 2 inches of the soil surface. Thus a volume of soil hitherto unoccupied was explored. But these surface-absorbing roots were relatively few and, as at the earlier examination, surface tillage would have resulted in little root damage.

Branching in the second foot of soil was at the rate of three to nine laterals per inch. Although numerous rootlets were only a few millimeters long, others extended widely (Fig. 29). Many were fairly well rebranched. The younger portions of the roots, which occupied the third foot of soil, were furnished with only short branches. On the deeper, main vertical roots, branches were only 0.1 to 2 inches long below the 2-foot level. As shown in the drawing, their occurrence was somewhat irregular, a distribution usually explainable upon the basis of soil texture.

The roots were slightly yellowish in color and hence the smaller ones were difficult to follow in the clayey subsoil. When they were broken, large drops of sap soon collected on the ends. This

was more noticeable in the cabbage than in most other plants The cabbage taste was characteristic of all the roots, even the still rapidly growing root ends Although the rows were 40 inches apart, no soil space was unoccupied In fact at this time considerable overlapping of the territory occupied by the plants in the adjacent rows and especially by plants in the same row occurred

Mature Plants —A final examination was made Aug 4 The plants were over 1 foot tall, had a spread of more than 2 feet, and possessed firm, well-matured heads In addition to the buds or

FIG 30 —A fully grown cabbage plant showing the large leaf surface which was 34 square feet

heads about 22 large green leaves per plant were present More than a dozen dead leaves clothed the base of the stem Thus there was presented a very large transpiring area, approximately 34 square feet, to the hot, dry, midsummer air (Fig 30)

To provide sufficient water and nutrients for the tops, the root system, already so well distributed in June, had greatly extended its range and fully ramified the soil The soil was drier in the cabbage plat than in the adjacent, unplanted area This was very noticeable even to a depth of 5 feet Compared to the water content in the beet plats (p 12), the surface foot was drier (often 3 to 5 per cent) at all times. At greater depths,

however, there was usually less water available in the plats of beets

A few of the main vertical roots had greatly increased in length, a maximum depth of 7 8 feet being attained The last 8 to 12 inches of roots were quite unbranched In fact, below 3 feet the branches were short, ranging between 0 2 and 1 inch in length Branches 2 to 3 inches long were occasionally found They occurred at the rate of five to nine per inch and were usually simple These deeper roots were quite sinuous in their course In the harder, calcareous soil of the fourth foot, the zigzag course was most pronounced

The maximum lateral spread was scarcely greater than at the previous examination, about 3 5 feet on all sides of the plant But within the soil volume thus delimited a wonderful root development had occurred The abundant main roots, which ran at various oblique angles (Fig 29) and had reached a working level of 32 inches on June 24, now attained 62 inches Thus the volume of soil ramified by the roots was nearly doubled The depletion of the soil moisture at this depth is clearly apparent (p 12) The roots were very abundant to the 62-inch level, being found in almost every cubic inch of soil They were somewhat fewer just above this level and were scarce below 62 inches

Branching in this new soil volume was profuse but scarcely so extensive as in the first 2 5 feet Some differences in branching habit were clearly related to soil structure The very hard, dry soil of the second foot, particularly, was not so well filled with rootlets Here, too, the roots were much more curved and crooked, undoubtedly due to difficulty in penetrating the soil On the best-branched portions of the root system laterals occurred at the rate of 15 to 20 per inch They were rebranched at the rate of 10 to 12 per inch, these being branches of the fourth order

A fair conception of the remarkable absorbing system of cabbage may be gained by a study of Fig 29 It should be kept in mind that in this late stage of development branching is much more profuse than here pictured, and that a somewhat similar, although less profuse, network of roots extended to a depth of 5 feet This filled most of the space here delimited by the widely spreading laterals In fact the soil had been so depleted of its moisture—or perhaps this was due partly to the age of the plants—that some of the rootlets were beginning to wither and die.

Summary.—Copenhagen Market cabbage is characterized by a very extensive, fibrous, finely branched root system. When the taproot is injured in transplanting, one of the long laterals usually assumes the position of a taproot. It is usually no more prominent, however, than many of the other major laterals that arise in great numbers from the base of the enlarged underground part. At first nearly the entire root system consists of widely spreading branches in the surface foot of soil. Later these run obliquely downward and with other more obliquely and vertically descending laterals thoroughly occupy the deeper soil. A maximum lateral spread of 3.5 feet is attained about the time the heads are two-thirds grown, but the depth of the root system in the soil thus delimited is thereafter doubled. Mature plants have a working level of 5 feet, to which depth the soil is well ramified with a profuse network of absorbing rootlets. Thus a single plant draws upon more than 200 cubic feet of soil for water and nutrients.

EARLY FLAT DUTCH CABBAGE

The Early Flat Dutch variety was studied at Norman, Okla. The plants were spaced 2.5 feet apart in rows 3.5 feet distant. Cultivation was very shallow so as not to injure the roots.

Mature Root System.—The root system of small but mature plants was quite similar in character to that just described but in extent it more nearly approached that of the June 24 examination. The strong, cord-like laterals were just as abundant and quite as well branched with delicate laterals. A maximum spread of 33 inches and a maximum depth of 46 inches were attained.

Seed Cabbage.—Plants grown the preceding summer lost their leaves during late summer, but these were replaced in the fall by new leaves, about 3 inches long, developed from the stem. The tops made practically no growth until spring and no new roots had developed. On Mar. 1 the plants were uprooted and then reset in a manner similar to that practiced in raising cabbage for seed. Conditions were favorable for root establishment, and by the end of the month a dense network of fine roots had developed from the old root-stem axis and from the broken laterals left on the plants in resetting. Typical plants had 18 to 35 strong laterals about 1 millimeter in diameter and 11 to 14 inches long. In addition 200 to 300 roots about 0.5 millimeter thick and 5 to 6 inches long had developed. These roots either turned downward

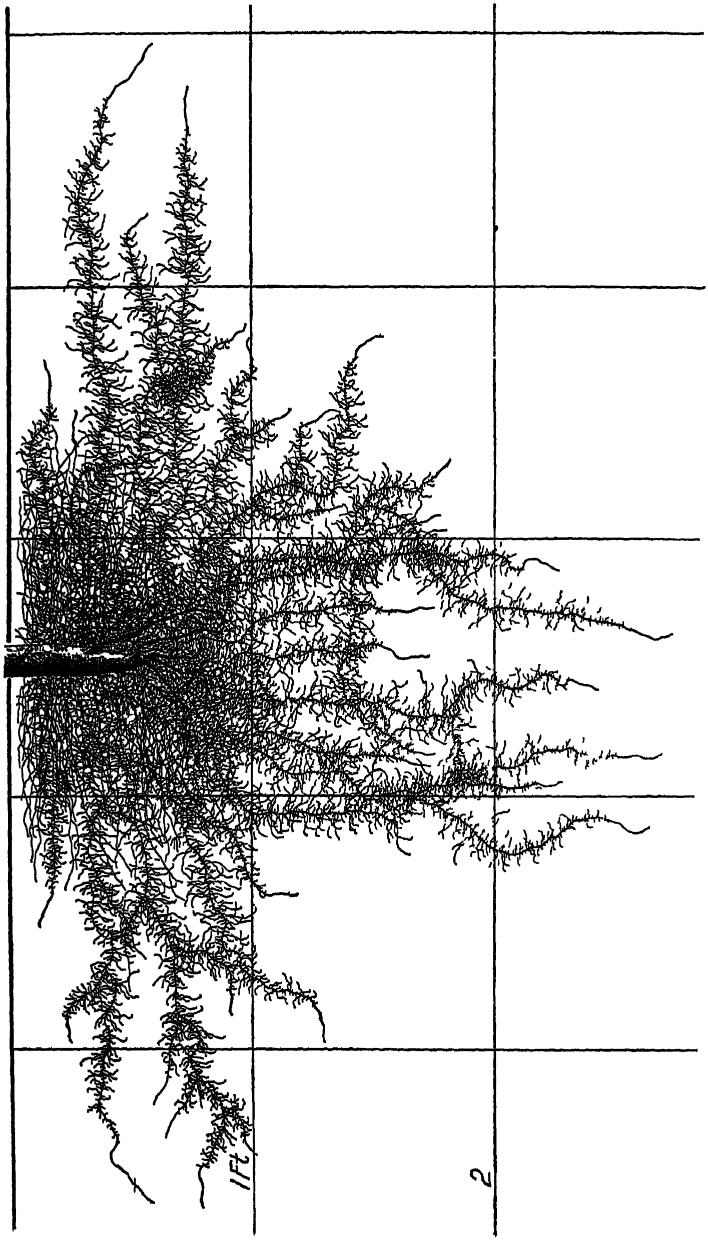


Fig. 31.—A portion of the root system of a cabbage plant reset the second year for the production of seed. The old root system has been replaced by a new one of a quite different type.

or grew in a somewhat horizontal direction through the moist, mellow soil All of the new roots were very fine and the older portions well branched Laterals reaching 4 inches in length occurred on the older parts at the rate of 6 to 12 per inch

The plants had nearly finished blooming by May 8 The larger basal leaves were dead but the cauline leaves were quite green The tops consisted of 20 to 30 main branches with long terminal racemes The height varied from 2 to 3 feet

The root system was extremely fine and fragile, making excavation very difficult Moreover, branches were so numerous that it was impossible to show the entire root system in a plane Hence, only a part of it was drawn in Fig 31 This shows the dearth of roots in the 3 inches of surface soil, except directly beneath the plant, also the wide lateral spreading of the horizontal roots in the surface foot (the maximum was 36 inches), a spread of 12 to 18 inches in the second foot, and the unbranched root ends in the deeper soil The greatest depth was 33 inches The long, rebranched laterals intermixed with the shorter, mostly unbranched rootlets were characteristic The latter were mostly 0 5 to 3 inches long and usually pursued a course somewhat at right angles to the roots from which they originated

Summarizing, Early Flat Dutch cabbage has a root system similar in habit but less extensive than that of the Copenhagen Market Plants reset for seed develop a very dense, fibrous root system which occupies a conical soil volume nearly 5 feet in diameter and 2 5 feet deep

Development of Roots and Tops as Affected by Cultivation — During 1926 experiments were conducted to determine the effects of deep and shallow cultivation upon root development of cabbage and its relation to the water and nitrate content of the soil The plants (Copenhagen Market variety), when transplanted into the field May 3, were placed in two plats separated by an uncropped area 10 feet wide Each plat consisted of 5 rows 40 feet long and 3 feet apart and the plants were also 3 feet distant in the rows The field was an almost level lowland and the soil a moderately rich silt loam Hence, the plants made a good growth notwithstanding a dry summer In fact April, May, June, and July each had a precipitation below the normal, the total deficiency amounting to 4 4 inches During these months (Apr 1 to Aug 5) only 16 showers in excess of 0 15 inch occurred The year was also characterized by a late, cold spring

One plat was hoed 3.5 inches deep at five different periods, *viz.*, May 15 and 31, June 14 and 25, and, finally, July 11. On the same dates the other plat and the uncropped area were thoroughly scraped to a depth of ½ inch.

An examination of the roots in the two plats on June 19 revealed no differences in the size or direction pursued by the laterals in the surface foot of soil. The root systems were found to agree in all respects with those excavated the preceding year. Most of the roots occurred below the maximum depth of hoeing but some horizontal roots had been severed. In every case these were much more branched than similar, shallow, horizontal roots

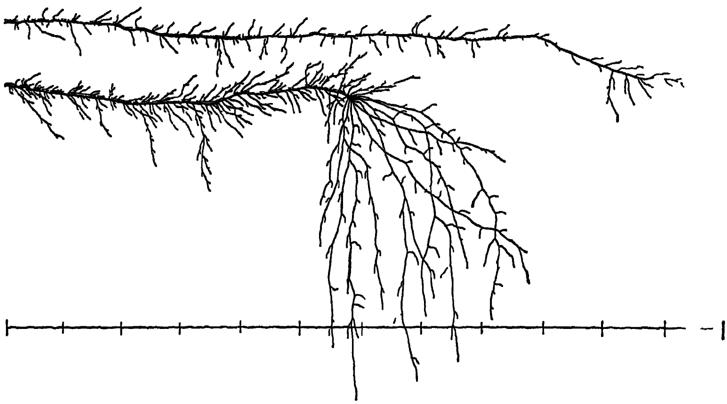


FIG. 32.—Representative surface roots of cabbage under two types of cultivation. The upper root shows normal development in the surface soil layer. The lower one has been cut by deep cultivation. This resulted in a great increase in branching. Scale in inches.

in the scraped plat. Moreover, from near the cut end a large number of long, rebranched laterals had extended downward (Fig. 32). Thus the chief direct effect of deep cultivation on the root system was to promote branching of the injured roots.

A later examination, July 28, revealed that the roots in the scraped plat extended to within ½ inch or less of the soil surface. Under the leaves that covered the ground for a distance of 1 foot on all sides of the plant the surface soil was moist and the roots came to within 2 millimeters of the surface. In the deeply hoed plats few or no roots were found in the surface 3.5 inches of soil except near the base of the plant where branches occurred from the cut root ends. The soil was fairly moist. The center of the

uncropped area was, in general, free from roots, although a few were traced two-thirds of the distance across this 10-foot strip

A study was made of the moisture content of the soil of the two plats and that of the uncropped but scraped, intervening area Samples were taken in duplicate at the several depths at each determination These data are given in Table 13 An examination of this table reveals the following facts In both of the plats sufficient water at all times was available to promote good growth After the roots became widely spread between the rows, where the samples were taken, the water content in the deeply hoed plat became gradually less than that in the middle of the uncropped area This decrease in soil moisture was in general progressive throughout the season and as the roots extended deeper it became marked even at depths below 2 feet A decrease of 2 to 4 per cent was common in the surface foot, although it was sometimes more than twice these amounts Moisture content of the scraped and uncropped area was also uniformly much greater at all depths than that in the scraped and cropped plat Differences of 3 to 5 per cent were common in the surface soil and 2 to 5 per cent below the first foot These differences indicate the large amounts of water removed from the soil and subsoil by a crop of cabbage

A comparison of the deeply hoed and scraped plats shows that water content in the former was, with one exception, constantly higher at all depths to 2 feet Differences of 3 to 4 per cent in favor of the deeply cultivated plat were frequent and they were sometimes more marked At greater depths similar marked differences occurred later in the season when absorption in the deeper soil was vigorous The greater water content in the surface soil was due in part undoubtedly to the soil mulch afforded by deep hoeing during this year of drought and partly to the absence of roots in this soil layer The greater exhaustion of the water in the deeper soil in the scraped plats may have been due to a better development of the deeper portion of the root system During the latter part of July and in August, it was clearly evident that the deeply hoed cabbage was not making the same vigorous growth as that in the scraped plat The cabbage in the scraped plats had the advantage of utilizing the nutrients in the surface 3 or 4 inches of soil, which was the richest part of the substratum

TABLE 13.—APPROXIMATE AVAILABLE WATER CONTENT, *i.e.*, AMOUNT ABOVE THE HYGROSCOPIC COEFFICIENT, IN THE SEVERAL PLATS AT LINCOLN, NEB., 1926

Date	Depth, feet	Un-cropped, scraped soil	Cropped, deeply hoed soil	Cropped, scraped soil	Excess water of uncropped over cropped, scraped soil	Excess water of uncropped over cropped, deeply hoed soil	Excess water of cropped, deeply hoed over cropped, scraped soil
June 9	0.0–0.5	10.7	13.9	10.5	0.2	−3.2	3.4
	0.5–1	15.0	15.1	11.8	3.2	−0.1	3.3
June 17	0.0–0.5	13.3	13.7	10.1	3.2	−0.4	3.6
	0.5–1	16.0	15.1	13.0	3.0	0.9	2.1
	1–2	15.2	15.4	13.7	1.5	−0.2	1.7
June 25	0.0–0.5	9.0	11.3	4.0	5.0	−2.3	7.3
	0.5–1	16.0	14.3	10.3	5.7	1.7	4.0
	1–2	14.8	14.3	12.2	2.6	0.5	2.1
	2–3	12.7	11.4	11.4	1.3	1.3	0.0
July 2	0.0–0.5	5.0	3.0	1.5	3.5	2.0	1.5
	0.5–1	14.1	9.6	11.3	2.8	4.5	−1.7
	1–2	13.9	12.3	11.6	2.3	1.6	0.7
	2–3	11.1	10.2	10.8	0.3	0.9	−0.6
July 9	0.0–0.5	19.0	8.8	5.1	13.9	10.2	3.7
	0.5–1	10.5	8.7	5.2	5.3	1.8	3.5
	1–2	14.4	11.8	9.7	4.7	2.6	2.1
	2–3	12.4	12.2	7.4	5.0	0.2	4.8
	3–4	12.8	10.0	9.6	3.2	2.8	0.4
July 19	0.0–0.5	8.6	6.3	1.1	7.5	2.3	5.2
	0.5–1	12.6	4.2	2.6	10.0	8.4	1.6
	1–2	12.8	9.6	6.1	6.7	3.2	3.5
	2–3	11.6	10.3	5.1	6.5	1.3	5.2
	3–4	11.4	9.6	9.2	2.2	1.8	0.4
July 28	0.0–0.5	9.7	6.0	5.4	4.3	3.7	0.6
	0.5–1	12.8	5.5	4.1	8.7	7.3	1.4
	1–2	12.9	5.6	4.2	8.7	7.3	1.4
	2–3	11.3	6.5	4.1	7.2	4.8	2.4
	3–4	11.6	5.9	8.4	3.2	5.7	−2.5

Experiments at Ithaca, N. Y., on the effects of cultivation on soil moisture and yields of vegetable crops gave similar results. No benefits were derived from cultivation, the yields being greater on scraped than on cultivated plats.[152,158] These studies, when extended over a period of six years, showed the average yield to be about the same under the two types of cultivation.[159a]

Determinations of nitric nitrogen were made on the several dates shown in Table 14. At every determination the amount was greatest in the uncropped soil; in fact, it was often twice the amount found in the cropped plats. After July 3, when the root systems were well developed, the differences were very marked. No consistent differences were found between the nitrate content of the soil in the deeply cultivated and scraped plats.

TABLE 14—NITRIC NITROGEN IN PARTS PER MILLION IN THE SEVERAL PLATS, 1926

Date	Depth, inches	Uncropped area	Deeply hoed	Surface scraped
June 2	0–6	33.5		16.3
June 9	0–6	31.0	20.1	26.0
June 19	0–6	38.5	15.0	29.6
	6–12	21.2	7.4	12.1
July 3	0–4	34.6	17.3	12.9
	4–12	18.9	6.8	12.6
	12–24	6.8		6.0
July 10	0–4	39.5	7.5	4.7
	4–12	21.4	3.9	1.9
	12–24	6.8	2.2	1.3
July 19	0–6	47.0		13.8
	6–12	16.1		11.8
	12–24	7.1		4.4

These results are in accord with those obtained at Ithaca, N. Y., where soil samples were taken at intervals of approximately two weeks during the growing season to a depth of 18 inches. They were obtained from several plats of cabbage, beets, carrots, onions, tomatoes, and celery and from fallow soil. "With the cropped areas the differences in nitrates between the cultivated and the scraped plats were not significant except with the trained tomatoes, where the cultivated soil averaged higher than the scraped soil."[159a] As regards the cultivated and scraped fallow plats a slight increase in nitrate nitrogen was found in the former.

Other Investigations on Cabbage.—In the preceding investigation in New York,

> roots were found to a depth of 30 inches, even the finer roots being found in considerable numbers as deep as 24 inches. A large part of the root system, however, was found in the surface 12 inches which corresponded to the depth of the surface soil. The roots extended laterally as far as 3 feet and were about as plentiful midway between the rows as within a few inches of the plant. The roots were branched many times so that the soil was quite thoroughly filled to the depth of 6 inches, although the greatest mass was found within 3 inches of the surface. Most of the cabbage roots were quite small, but of about the same size throughout their length.[152]

Further studies on cabbage (Cophenhagen Market variety) at the same station are of interest. Twenty-five days after the

plants had been transplanted into the field, they were stocky, 4 inches high, and had a total spread of 6 inches The roots were 10 inches deep and the soil within a radius of 8 inches was well filled with fibrous roots, many of which were within an inch of the soil surface Twenty days later, on half-grown plants, the soil was well filled with fine branching roots to 15 inches depth, some extending to the 22-inch level Lateral roots had reached the centers between the 3-foot rows and the surface soil was well filled with fine roots to a distance of 12 inches from the plant The roots grew rapidly and when the plants were fully grown had reached a depth of 3 feet The soil was well filled with fine roots to a depth of 30 inches Many roots were traced to adjoining rows The main laterals, which were of nearly the same size throughout, grew almost horizontally The roots were extremely well branched and so filled the surface soil that cultivation could not be given without destroying large numbers of them

A study of the root system of a mature Very Early Etampes variety of cabbage at Geneva, N Y, revealed that the fibrous roots lie chiefly in the upper layers of the soil, some approaching very near the surface although they also penetrate to a considerable depth In this small, early variety, a lateral spread of about 18 inches and a depth of penetration of 20 inches were attained [43] Since the plant was washed from the soil it is quite probable that the entire root system was not recovered

Investigations in Germany have shown that the root system of cabbage is widely spreading, strongly branched, and deeply penetrating The adventitious roots arising from the stem supplement the main root system Depths of penetration of 4 to 5 feet were ascertained [89]

Relation of Root System to Cultural Practice.—The very extensive and finely branched root system of cabbage, together with the extensive development of the tops, helps to explain why it is "hard on the land" Compared with beets, for example, under the same type of cultivation, Table 2 shows that cabbage much more thoroughly exhausts the water supply in the surface foot of soil, the place where its roots are most abundant From May 29 to Aug 13 an excess-moisture supply of 2 to 9 per cent in favor of the beets was ascertained This intensive absorption by the shallower portion of the root system helps to make clear why on a good loam soil frequent shallow irrigations 8 to 10 days

apart, particularly after the cabbage begins to head, result in larger yields than heavier irrigations at longer intervals [33] Indeed, it is very dependent upon a proper supply of water and suffers more from a lack of it than most garden crops The roots also need good aeration, in wet soils the plants turn yellow and cease growing The roots must also supply the plant with a large amount of nutrients, especially nitrogen and potassium, to develop the large, succulent leaves The time of application of the fertilizer influences both the time of maturity and the total crop yield In fact, cabbage soil can hardly be made too rich if the food materials are in a well-balanced form Thus it is easily understood why, although early varieties do well on light soils, late-maturing crops, to give high yields, must be grown on clay-loam or silt-loam soils, preferably those with considerable humus, where both water and nutrients are constantly abundant This results in a uniform, continuous growth If the heads, because of lack of moisture, cease growing when nearly mature and again start growth as a result of rains or irrigation, they are very likely to crack This bursting is due to the absorption of excessive moisture by the roots It may be prevented by pulling on the stem sufficiently to break a part of the roots or by deep cultivation

Cultivation —The superficial position of many of the very long, horizontal roots of the cabbage and its habit of thoroughly occupying even the surface 1 or 2 inches of soil show clearly why cultivation should be shallow Root growth is better and cultivation easier when the soil has been deeply plowed and well prepared

Experience has shown that cabbage requires considerable room to develop properly Consequently, plants are spaced, depending upon the variety, 1 to 2 feet apart in rows 2 to 3 5 feet distant But after only a few weeks of growth the roots overlap between the rows and the soil is thoroughly ramified There is no place for competing weeds and sufficient cultivation should be given to keep them out and perhaps to maintain a soil mulch until the roots rather thoroughly occupy the soil

The plants respond to good cultivation by vigorous growth of roots and tops They will not tolerate neglect like many other vegetable crops Later cultivation is sure to cut many of the roots and thus decrease the absorbing area As already indicated, this results in decreased yields Like the soil in a field of sweet corn, it is so thoroughly occupied by roots that little water is lost by direct evaporation In fact, the effect of a soil

mulch in conserving moisture appears to have been greatly exaggerated in popular literature on gardening

Under some conditions a soil mulch conserves moisture while under others it has the opposite effect Even where moisture is conserved by a soil mulch the advantages may be lost because of injury to the roots by cultivation when the plants are large and the root system well developed Plants having a large and well-distributed root system respond less to cultivation, for purposes of maintaining a soil mulch, than plants with a relatively small and restricted root system There is also less moisture conservation from cultivation with the former than with the latter type of root system [158]

Transplanting—The common practice of the successful transplanting of seedlings into the field is closely connected with root development When it is recalled that transplanted crops such as cabbage, cauliflower, sweet potatoes, tomatoes, celery, peppers, eggplant, and Brussels sprouts comprise over half the acreage and value of all vegetables (other than Irish potatoes), the importance of the process may be appreciated [97]

Transplanting consists in lifting the plant from the medium in which its roots are established and in replanting in a different location It is a violent operation because the younger roots with their root hairs are, as a rule, sacrificed in the process of lifting This is just the part of the root system most active in absorption Taking up plants for transplanting results not only in breaking many of the roots but also especially in injury to the taproot As a consequence many new roots are formed These do not grow so long as the original ones They form a more compact root mass about the base of the plant Hence, the root system is less disturbed when the plant is finally transplanted into the field Thus, although the root system of transplanted plants may be less extensive than that of undisturbed ones, upon removal to the field the transplanted plant carries more roots with it and consequently more readily reestablishes itself

Recent investigations throw much light upon the results obtained by different methods of transplanting vegetable crops * Like many old-world practices brought to America, such as pruning and suckering, excessive cultivation, and too heavy fertiliz-

* Many of the data on transplanting have been abstracted from the excellent paper Loomis, W E, "Studies in the Transplanting of Vegetable Plants"

ing, methods of transplanting have heretofore been accepted without adequate investigation Because of the excellent tilth and fertility of virgin soils the growing of vegetable crops has been generally prosperous in spite of these practices some of which, however, have been gradually eliminated either as being unnecessary or injurious

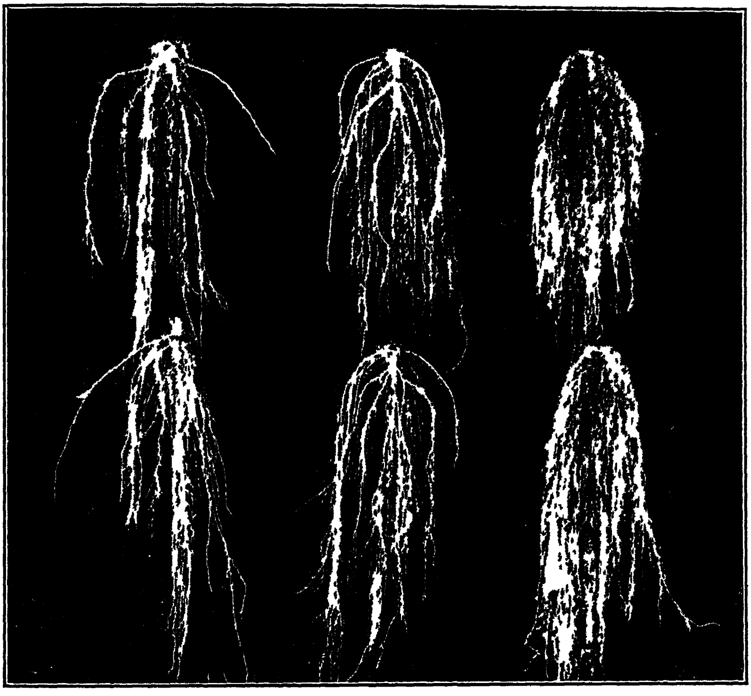


FIG 33 —Effects of transplanting on the root system of cauliflower Left, not transplanted, center, once transplanted, right, twice transplanted Photograph taken as "heads" were forming (*After Loomis, Cornell Univ Mem* 87)

One of the chief arguments nearly always advanced in favor of transplanting is that the branching of the root system is increased as a result of the root pruning That the roots of transplanted plants are more branched than those not transplanted is shown in Fig 33 The tendency of transplanted cabbage to retain balls of earth with their roots as well as the development of the root system itself are shown in Fig 34 Thus it is possible to transfer a good ball of earth with twice transplanted cabbages, for example, while the roots of plants not transplanted are practically

bare Although transplanting was formerly considered beneficial in itself, it is gradually coming to be recognized as an expedient not directly promoting the development of the plant

Although strongly recommended by the older gardeners and many of the earlier writers on the subject of vegetable growing there seems at present to be considerable doubt in the minds of growers concerning

FIG 34—Effects of transplanting upon the root system of cabbage and the tendency to retain earth about their roots Left, not transplanted, center, once transplanted, right, twice transplanted (*After Loomis, Cornell Univ Agr Exp Sta, Mem* 87)

the advisability of giving more transplantings than are required in the most economical production of the crop That is, the tendency is away from transplanting as a cultural practice toward transplanting as a matter of economics Certain crops, as early lettuce and cabbage or tomatoes, are transplanted in order to grow them out of the normal season for a given locality Tomatoes, sweet potatoes, and similar vegetables may also be grown in higher latitudes if the plants are started with artificial heat The use of artificial protection usually

requires transplanting, because it is most convenient to have the plants concentrated into a small area while the protection is being given. The same is true when special care in cultivation, watering, protection from insects, and so forth are required by the seedling plants. A third factor, which accounts for most of the transplanting in greenhouses and some of that done in intensive cultivation, is the saving of space and of expensive seeds. For these reasons transplanting will be practiced as long as profitable crops can be produced by the method. On the other hand, it is an expensive operation and not to be performed unnecessarily.

Experiments have shown that the general effect of transplanting is to retard development. The growth of young plants may be arrested without serious injury but the effect of equivalent checking increases with the maturity of the plant. The degree of retardation varies with the kind of plant, its age, and the conditions of transplanting. Cabbage is one of a group of plants, in which are also included tomatoes, lettuce, and beets, that easily survives transplanting. Peppers, onions, celery, and carrots are transplanted with more difficulty and a third group consisting of such species as corn, beans, melons, and cucumbers are very difficult to transplant successfully except at a very early age. In fact with advancing maturity injury from transplanting increases in all cases. A single transplanting at a later stage of development may do more injury than two or three earlier transplantings. Hence, transplanting at the proper time is one of the most important features in growing vegetable crops. There is a rapid decline in the rate of root replacement with increasing age.

The immediate effect of transplanting is to slow down or stop the growth of the plant for a period which seems to vary directly with the amount and duration of the reduction of the water supply. The rate of new root formation is the most important consideration in the reestablishment of transplanted vegetable crops. When a large proportion of the root system is retained and adequate moisture supplied, there may be very little harmful effect from transplanting.

Recovery from transplanting is affected by a large number of environmental and internal conditions. Among these are the amount of suberization of the older roots, the proportion of the root system normally retained in transplanting, the rate of new root formation, and adaptation of the tops (by hardening, etc.) to prevent water loss or increase resistance to death by sudden

wilting In addition to these are the environmental factors of soil moisture, humidity, temperature, wind, etc But all appear to be based in their final effect upon a change in water supply of the plant Experiments have shown that the most important factor involved in resistance to transplanting or recovery is the root Cabbage and other easily transplanted plants, as compared with corn, melons, etc, retain a relatively larger proportion of their root system when transplanted (a fact due in part to their network of fine branches), the retained roots are much less suberized and consequently more efficient absorbers, and the rate of new root formation is much greater

The practice of growing plants in pots, small boxes, cans, or plant bands is advantageous inasmuch as the root system is little disturbed in setting the plants into the field, since practically all of the roots remain in the ball or block of soil Likewise, they may be shifted from one receptacle to another of larger size with little or no injury to the roots

In transplanting cabbage the leaf area is often considerably reduced so that transpiration will not be too great [100] This is accomplished by gathering the leaves of the plants together and shearing the upper portion, care being taken not to injure the buds The transplanting of smaller plants, however, would seem more advisable [33] Although the ratio of roots to tops may fluctuate widely for a short period after transplanting, it tends to come to an equilibrium which is dependent upon the balance between growth and food supply in the plant, *i e*, the supply of water and soil nutrients to the tops and elaborated food to the roots Further studies of these subjects are needed

The advantage of using only the strong, stocky plants has been fully demonstrated As a result of an experiment in Pennsylvania extending through a period of 3 years, it was found that small plants for the late crop gave a yield of only 12 7 tons per acre, plants of medium size 17 7 tons, and large plants 21 0 tons per acre Enkhuizen Glory and Danish Ballhead varieties were used and the plants were graded according to size at the time they were planted in the field [110]

Experiments have shown, contrary to general belief among gardeners and others, that transplanting in itself neither increases the yield nor hastens maturity These conditions result when decreased competition among the plants is brought about by giving each a greater space for growth Extensive experiments

in greenhouse and garden have shown that when transplanted plants are allowed no more space than those not transplanted, the effect of transplanting was, in every instance, a reduction in the yield For example, when cabbage was grown in the field and alternate plants in the row taken up and reset in the same place, the yield of 19 heads was 119 3 pounds as compared to 132 6 pounds from a similar number of plants not transplanted An experiment conducted in the greenhouse gave similar results

8 plants not transplanted weighed	4,214 0 grams
8 plants once transplanted weighed	2,993 5 grams
8 plants twice transplanted weighed	2,241 7 grams

Thus plants once transplanted yielded 28 9 per cent less and those twice transplanted 46 8 per cent less than those whose root systems were not disturbed Similar results were obtained with two varieties of cabbage and with cauliflower, tomatoes, and lettuce [29]

Relation of Roots to Competition and Disease —Competition among cabbage plants must be entirely below ground and in connection with the root systems, for the widely spaced plants will not shade each other considerably Hence, attention in spacing should be fixed upon root habit in the various types of soil in connection with the size of head desired and methods of cultivation

Certain diseases are closely related to root development Clubroot is due to a parasitic slime mold (*Plasmodiophora brassicae*) which attacks not only cabbage but plants related to it such as cauliflower, kohl-rabi, turnip, rutabaga, etc The roots become enlarged and malformed and fail to function normally As a result the plant is subject to wilting during periods of high transpiration The plants do not thrive and yields are greatly reduced, if indeed the plants do not die Root knot is a somewhat similar malady, common in the South, caused by a parasitic eelworm It may affect all kinds of vegetable crops In cabbage yellows, a soil-inhabiting fungus gains entrance through the root hairs, pushes back through the cortical tissue, and grows throughout the vascular system These invasions of root and stem result in diminution of water and supplies of food materials from the soil, which, in turn, give rise to stunted plants The host may be killed in the seedling stage or wilt and die at any time

during its growth. The leaves have a pale, lifeless, yellow color. Sometimes only one side of the root system is seriously attacked. Then the opposite side of the plant grows more rapidly and brings about a curving of stem and leaves. Both root and stem are greatly dwarfed. The majority of the diseased plants continue a sickly existence for a month or more and then succumb.[73]

Investigations have shown that disease resistance and predisposition to disease may largely depend upon environmental conditions under which the plant is developing.[72] By selecting plants whose roots are resistant to the fungus attack or ensuing injury, cabbage yellows has been brought under control.[74] These facts suggest another reason for a thorough understanding of not only the morphological relation but also the structural changes and chemical composition of roots.

CHAPTER XII

CAULIFLOWER

Cauliflower (*Brassica oleracea botrytis*) is a cole crop very closely related to the cabbage It is a variety of the same species, both having originated, probably as mutants, from the same wild-cabbage ancestor The cabbage head is a bud, but that of cauliflower consists of fleshy peduncles, pedicels, and other flower parts subtended by a number of cabbage-like leaves Cauliflower does not thrive in hot, dry weather and consequently is grown either as an early or late crop [63] It is not as hardy, can stand less heat, and is much more exacting as to climate than cabbage Hence, on a large scale it is grown only in a relatively few restricted areas in the United States

Seedlings of the Early Snowball variety were transplanted into the experimental field at Norman, Okla , Apr 19 The plants, which were in the third- to fourth-leaf stage of development, were set in rows 2 5 feet apart and 3 feet distant

Early Development —The first root excavations were made May 10 The plants had made a vigorous growth There were 6 to 8 leaves, 3 to 4 inches long, per plant The taproot, as usual, had been broken in transplanting The root system consisted of a large number of delicate white roots less than 1 millimeter in diameter As shown in Fig 35, many of these ran horizontally just beneath the soil surface, some to a distance of 15 inches Others ran outward and downward and still others descended almost vertically The greatest depth was 15 inches Laterals 2 to 4 inches long had grown from the older parts of the largest roots at the rate of 8 to 16 per inch Some of these gave rise to short sublaterals A similar branching rate was evident throughout the plant, but tertiary branches had not yet been formed on most of the rootlets The thorough occupancy of the surface soil was possible because of very shallow cultivation

Half-grown Plants —The plants grew vigorously and by June 15 the stems were over 0 5 inch in diameter and the plants 1 foot tall Leaves were abundant but "heading" had not begun

Typical plants had 6 to 10 main roots which were 1 to 3 millimeters in diameter Due to frequent branching they tapered rapidly so that 18 inches from their origin they seldom exceeded 1 millimeter in thickness Some extended widely in the surface foot of soil, others penetrated almost vertically downward, and still others pursued an intermediate course Hence, the general shape of the root system was that of an inverted cone with a diameter of about 2 feet at the base and a depth of 2 5 feet (Fig 36) All of the roots were profusely branched with both long and

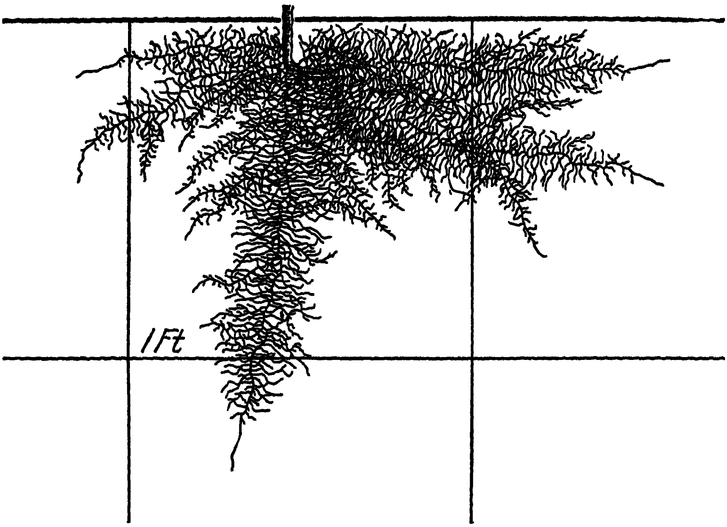


FIG 35 —Root system of Early Snowball cauliflower 3 weeks after transplanting into the garden. Note the fibrous roots near the soil surface

short laterals The larger ones were usually 5 to 9 inches in length but a few 15 inches long occurred Near the base of the plant and especially on the larger branches rootlets, often 4 to 10, grew in clusters These root clusters were very numerous, frequently 12 to 15 occurring per inch of main root The rate of branching elsewhere was about 16 laterals per inch Thus the soil volume was exceedingly well ramified by an extensive network of delicate, white rootlets

Maturing Plants.—When the cauliflower was suitable for table use, July 19, further examination of the root system was made The plants were 2 feet high and had a spread of tops of 2 5 feet,

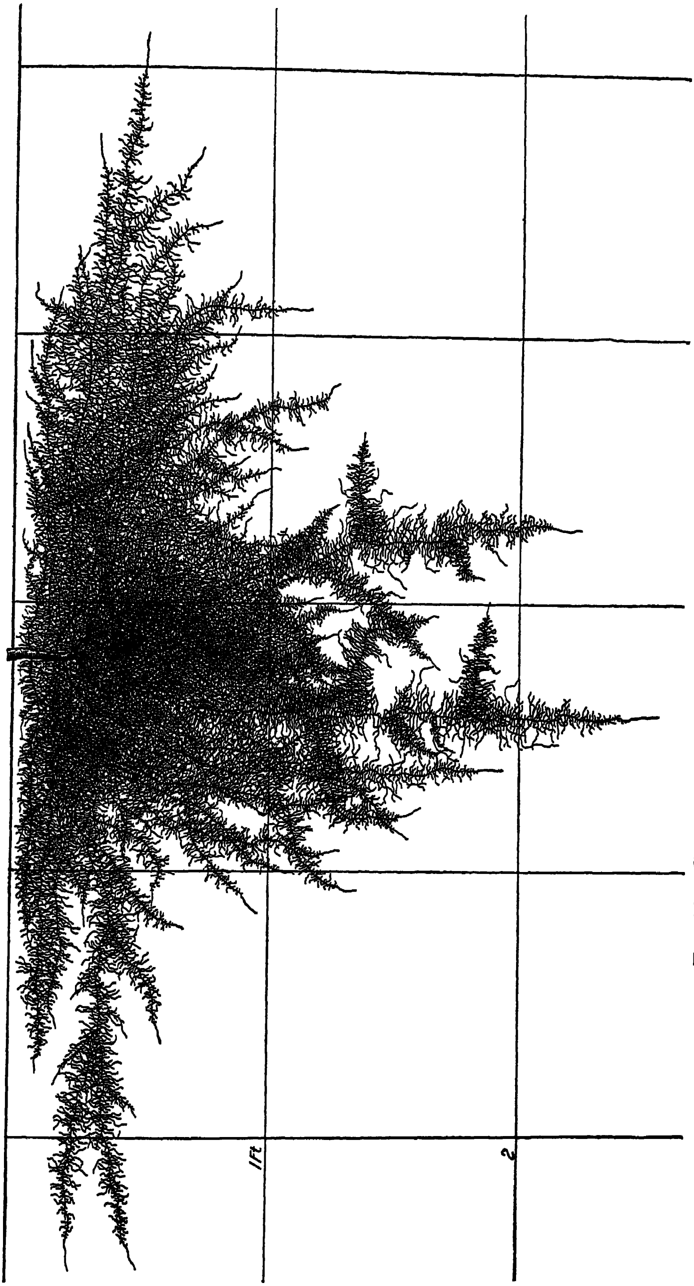


FIG 36 —Cauliflower 8 weeks after transplanting into the garden

A typical root system had 17 strong branches 3 to 10 millimeters in diameter. Few of them gave rise to major laterals until they had reached a distance of 6 to 12 inches from the base of the plant. Thereafter they branched repeatedly as shown in Fig. 37. The general shape of the root system had not been greatly changed except that a much larger soil volume in the second foot was now occupied. In this soil layer the lateral spread had been extended from about 8 inches (June 15) to 2 feet.

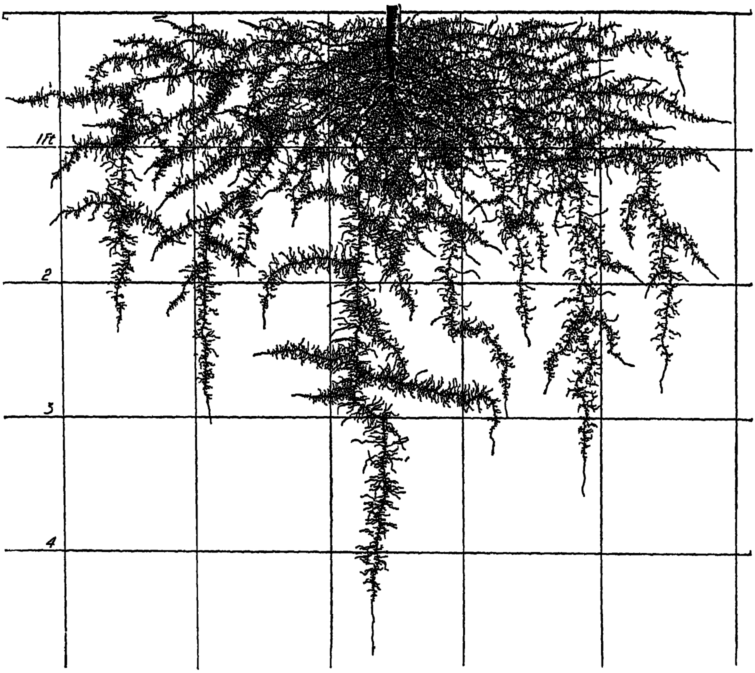


FIG. 37.—One-half of the root system of cauliflower (July 19) at the time the plants were suitable for table use.

The third foot of soil was also moderately well ramified, the deepest root, which had apparently replaced the taproot, reached the 54-inch level. The soil was also well occupied by rootlets near the surface. A lateral spread of 2.5 feet was found. Branching was even more profuse throughout the whole volume of moist, mellow soil than at the preceding examination. In fact, it is quite impossible to show the complete degree of branching in the most carefully executed drawing.

Summary.—Cauliflower, like cabbage, is characterized by a taproot which is usually injured in transplanting. Numerous, large, exceedingly well-rebranched laterals and a very profuse network of smaller ones occupy a large soil volume. Early in the development of cauliflower the soil from the surface to a depth of 8 to 12 inches is filled with fine roots throughout a zone with a radius of 1.5 to 2 feet. The 2 feet of soil beneath the plant is likewise well ramified. The widely spreading, main laterals finally turn downward. With their profuse network of branches, aided by those of more obliquely penetrating laterals, they thoroughly ramify the first 2 to 3 feet of soil throughout a territory extending 2 to 2.5 feet on all sides of the plant. The deeper soil to 4 feet is less fully occupied by vertically descending roots or branches. As a whole the root system even more thoroughly fills the soil than does that of cabbage.

Other Investigations on Cauliflower.—Few root studies have been made on cauliflower. It has been examined at Geneva, N. Y., and found to be a deeply rooting plant. Many roots were traced downward to a depth of 2.5 feet and some reached a depth of 3 feet. The horizontal root extent was 2.5 feet on all sides of the plant. Fibrous roots were less numerous in the upper layers of the soil than on tomato plants which were examined at the same time.[42]

Root Habits in Relation to Cultural Practice.—The root systems of cauliflower and cabbage have many similarities and the method of planting and growing cauliflower is very much the same as for cabbage. Climate is a more important factor than soil, the vigorous and extensive root system develops well in nearly all kinds of soil. Growth is promoted by thorough soil preparation and the liberal application of manure or other fertilizers. A constant supply of moisture for the roots should be maintained so that growth of the plants is never checked. This may be promoted by frequent tillage. Cultivation, as for cabbage, should be shallow. Because of the thorough occupancy of the surface-soil layers by the maturing root system, it would seem that, as in the case of cabbage, late cultivation might do more harm than good. All of the soil between rows spaced 2.5 to 3.5 feet apart is thoroughly occupied.

CHAPTER XIII

KOHL-RABI

Kohl-rabi (*Brassica caulorapa*) is a low, stout biennial, closely related to cabbage. Unlike cabbage and cauliflower it does not form a "head" but is cultivated for the fleshy stem which is produced the first season. This originates above the cotyledons, is short, 3 or more inches in diameter, and grows just above the ground. This vegetable is grown chiefly as an early spring crop, since it does not thrive during the heat of summer.

Seed of the Early White Vienna variety was sown Apr. 27, in rows 18 inches apart. Later the seedlings were thinned to 12 inches distant in the row.

Early Development.—The first examination was made June 10. The plants were characterized by strong taproots and numerous, nearly horizontal, widely spreading laterals in the surface 8 inches of soil (Fig. 38). Several of the main roots ended at depths of 2.5 to 3 feet. Just below the soil surface the slightly thickened taproots were clothed with very numerous, short, unbranched laterals which formed a dense network. Usually about 20 larger roots also arose in the first 10 inches of soil. Some were only 6 inches long, many extended outward 1 to 1.5 feet, and a few of the longest (usually about 6 inches deep) spread laterally 3 feet. These larger roots were furnished with an abundance of short, mostly unbranched laterals. They averaged less than 1 inch in length and occurred at the rate of about 6 per inch of main root. Below 8 inches, branches were fewer, especially between 8 and 16 inches, and mostly less than 1 inch long, although a few exceeded 5 inches and were quite well rebranched. Growth proceeded rapidly.

Later Development.—A second examination was made 20 days later, June 30. The thickened portion of the stems had a diameter of approximately 3 inches. The plants were 1 foot tall and each had about 18 large leaves. The large transpiring surface is indicated by the fact that the leaf blades averaged 7 inches in length and 6 inches in width.

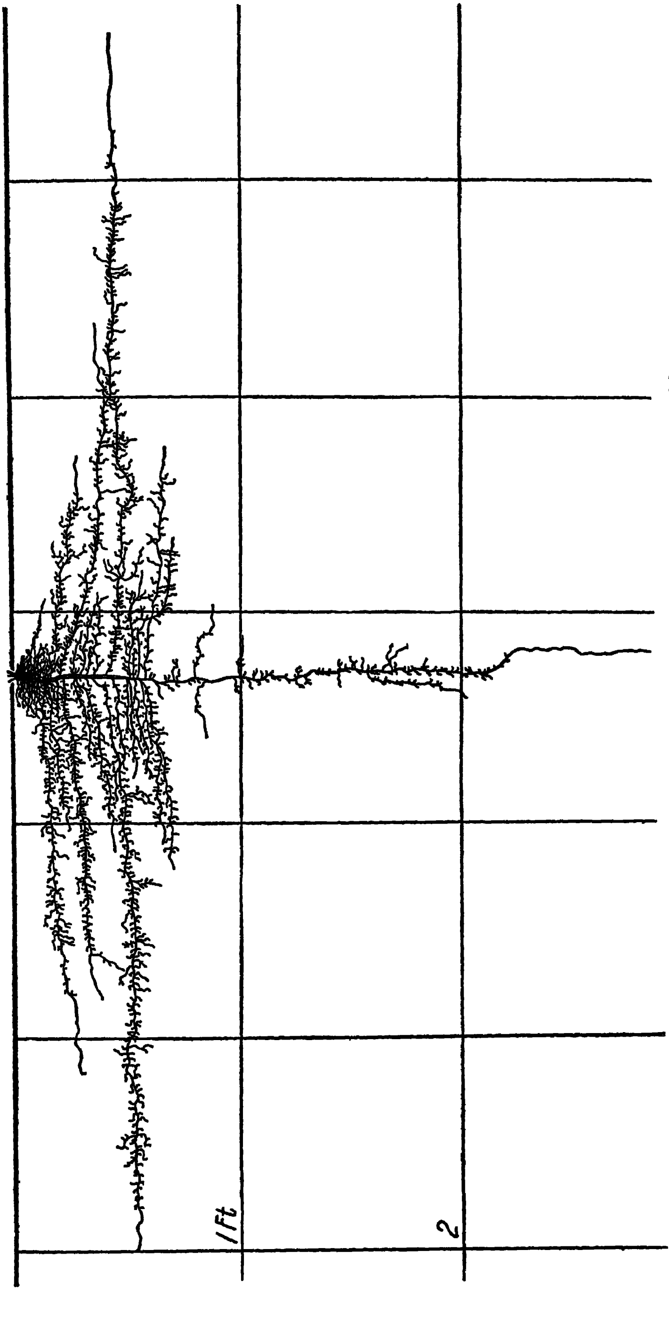


Fig 38 —Early White Vienna kohl-rabi about 6 weeks old

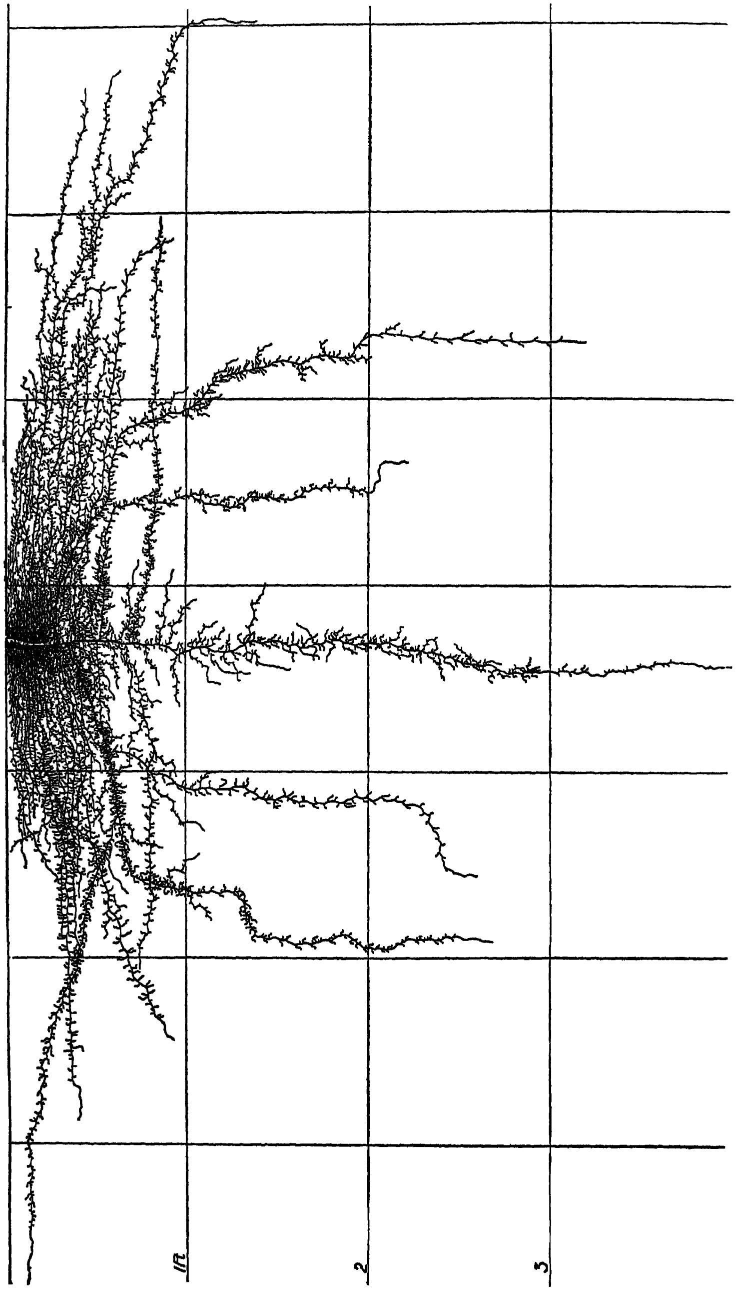


Fig 39 —Kohl-rabi 20 days older than that shown in Fig 38 Note the increase both in number and length of roots

During the 20-day interval the roots had grown considerably Moreover, the number was greatly increased Numerous counts showed that a typical plant had 81 nearly horizontal laterals in the surface inch of soil, 70 in the second inch, and 10 in the third Between 4 and 9 inches they occurred at the rate of about 6 per inch Although many of these did not exceed 3 to 6 inches in length, fully 20 per cent extended rather horizontally to greater distances, the longest having a total spread of 40 inches (Fig 39) The larger laterals had diameters of 2 to 3 millimeters

Near the plant, *i e*, for the first 4 to 8 inches of their course, the roots were extremely well branched, rootlets quite filling the soil Branching was at the rate of 12 to 20 laterals per inch They were 1 to 2 inches long and gave the main branches almost a woolly appearance The major portion of the laterals was furnished with branches 0 2 to 1 inch in length at the rate of 4 to 8 per inch Branches of the third order, although not long, were very common The main laterals also had large branches which ran in various directions, very often toward the soil surface (Fig 39) These were rebranched in a manner similar to that of the large roots Thus the surface 10 inches of soil to a distance of at least 2 feet on all sides of the plant were well occupied by roots Near the plant the roots occurred in dense masses forming a thread-like network That the horizontal branches were rapidly growing was shown by their long, thick, unbranched ends

Below the 10-inch level only a few roots were found Aside from the taproot these consisted of three to five of the obliquely descending laterals or horizontal ones which had spread 9 to 15 inches and then turned downward The smooth, unbranched ends of these were usually found between the second- and third-foot level Branching was abundant but not profuse Between the 10- and 18-inch level the taproots usually had about five branches per inch They varied considerably in their direction of growth but were seldom over 6 inches in length At greater depths the roots became shorter (3 inches or less) but were moderately well rebranched to near the 3-foot level Some of the taproots reached a depth of 4 feet A study of the root system clearly showed that the bulk of absorption was still taking place in the surface soil Tillage, except of the most superficial kind, would have been distinctly harmful to the roots

Mature Plants —At the time of the final examination, Aug 13, the plants had scarcely increased in size or number of leaves.

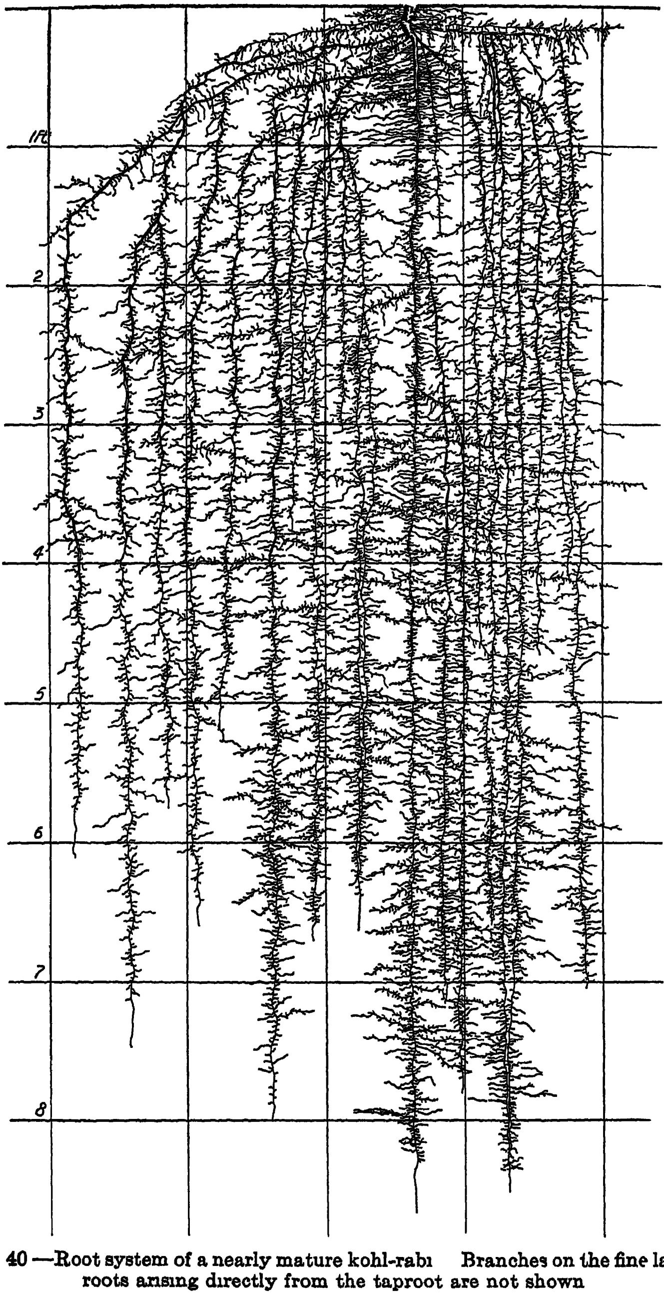


FIG 40 —Root system of a nearly mature kohl-rabi Branches on the fine lateral roots arising directly from the taproot are not shown

The leaves were somewhat larger, however (about 10 inches long by 7 inches wide) and the fleshy portions of the stem now had a diameter of 4 5 to 5 inches

The underground part had made a remarkable growth, especially in depth The lateral spread of any of the plants examined did not exceed that of the June examination The fleshy taproots frequently measured 1 7 inches in diameter near the soil surface but tapered to about half this diameter or less at the 6-inch level At greater depths they scarcely exceeded some of the larger laterals which were 6 to 10 millimeters in thickness They pursued a vertically downward course to a maximum depth of 7 to 8 5 feet This depth was also reached by a few of the rather vertically descending larger branches (Fig 40)

As at the earlier examinations, most of the larger branches arose from the first 10 inches of the taproot In general, the roots here were of two sizes There were small ones, usually less than 1 millimeter in diameter and only 1 to 6 inches long, and others distinctly larger and very extensive They originated from two sides of the taproot Frequently as many as 140 of the smaller laterals occurred on the first foot of the taproot They were profusely rebranched with rather long laterals which were again rebranched For the sake of clarity, the branches on these fine lateral roots have been omitted

The number of large laterals was variable, 6 to 10 being usual They ranged from 2 to 10 millimeters in diameter Usually they ran rather horizontally or obliquely outward 1 foot or more and then, turning downward, ended in the fifth to seventh foot of soil Others turned more directly downward so that the entire soil volume below the plant was quite well occupied As shown in the drawing, these large laterals often gave rise to strong branches All these main roots as well as the taproot, which also gave rise to a few large laterals in the deeper soil, were profusely furnished with fine branchlets They occurred at the rate of 5 to 10 or even more per inch and varied in length from 0 1 to 8 inches The longer ones, especially, were well rebranched In general, the small branches of the first order were rather horizontal They formed a close network in the soil to the working depth of 7 feet The roots were all in good condition and growth was still taking place

Summary —Young plants of kohl-rabi are characterized by a well-developed taproot and very numerous, shallow, but widely

spreading, horizontal branches. In this respect it is very similar to cabbage. By July 1 the surface foot of soil 2 feet on all sides of the plant is ramified by a dense network of rootlets. A few obliquely descending rootlets and the taproot extend into the third or fourth foot of soil. In mature plants the taproot below a depth of 1 foot scarcely exceeds in importance the 6 to 10 major branches or even some of their laterals which, after running outward, parallel its course. Both taproot and branches reach depths of 5 to over 8 feet. All are profusely furnished with fine, rebranched laterals, often of considerable length. From the dense network of short, surface branches to the working level at 7 feet, the soil is thoroughly ramified.

Other Investigations on Kohl-rabi.—Few investigations have been made on the root system of this plant. At Geneva, N. Y., the taproot of the Early Purple Vienna small variety was traced to a depth of more than 2 feet, having been followed through 14 inches of very compact clay. "Owing to the delicacy of the root we were unable to reach the end."[43] The horizontal roots extended 2 feet on all sides of the plant. As with cabbage and cauliflower, it was found that the fibrous roots were most numerous in the upper 8 inches of the soil.

Investigations in Germany have shown that the main mass of the roots of kohl-rabi are in the upper soil layers, but in the varieties of cabbage examined the soil was thoroughly ramified to a depth of 39 inches. Lateral spread varied from 3.3 to 4 feet.[89] These observations were made in the main by means of plants grown in containers, although also aided by observations from plants growing in the open, the root systems of which were carefully washed from the soil. Although it seems clear that differences in subsoil conditions greatly affect the depth of root penetration, it is equally certain that the roots of this plant may penetrate deeply.

CHAPTER XIV

TURNIP

The turnip (*Brassica rapa*) is a vegetable found in many home gardens throughout the United States Since it is a very hardy plant of rapid development but does not thrive in hot weather, it is usually grown either early in the spring or late in the fall in the North and as a winter crop in the South Although the large rosette of coarse, roughish leaves is sometimes used for "greens," turnips are usually grown for their enlarged fleshy roots The upper portion of this enlargement to which the leaves are attached is morphologically a stem During the second year of growth, or late in the fall of the same growing season, if planted in the spring, it produces a large, branched flower stalk 1 to 3 feet in height Thus the turnip is either an annual or a biennial

The Purple Top Globe turnip was planted June 16, 1 month too early for its best development, in rows 16 inches apart After the plants were well established, they were thinned to 6 inches distant in the row By July 10 they were 5 inches tall and had 5 to 7 leaves each The five largest were 3 to 4 inches long and 2 to 3 inches wide, thus presenting a rather large transpiring and photosynthetic surface

Early Development—The turnip is characterized by a strong taproot which was at this time 5 millimeters thick at the ground line but soon tapered to a diameter of 1 millimeter or less It pursued a somewhat tortuous downward course, making gentle curves through an amplitude of 1 to 3 inches Depths of 30 to 32 inches were attained by the taproots, the last 3 to 4 inches of which were unbranched The first 2 inches of taproot were also free from branches, there were 9 to 10 laterals per inch on the next 4 inches on typical plants Below this they varied from 6 to 12 per inch to near the root ends Thus a total of 200 to 225 branches occurred on a single plant (Fig 41)

It may be noted that most of the laterals in the surface foot spread somewhat horizontally At greater depths some ran more or less horizontally to only 1 to 3 inches and then turned

downward The longest branches and greatest lateral spread (about 14 inches) occurred in the first foot Practically all of the laterals were clothed with rootlets less than 0 1 to 0 3 inch long at the rate of two to five per inch On the largest laterals they

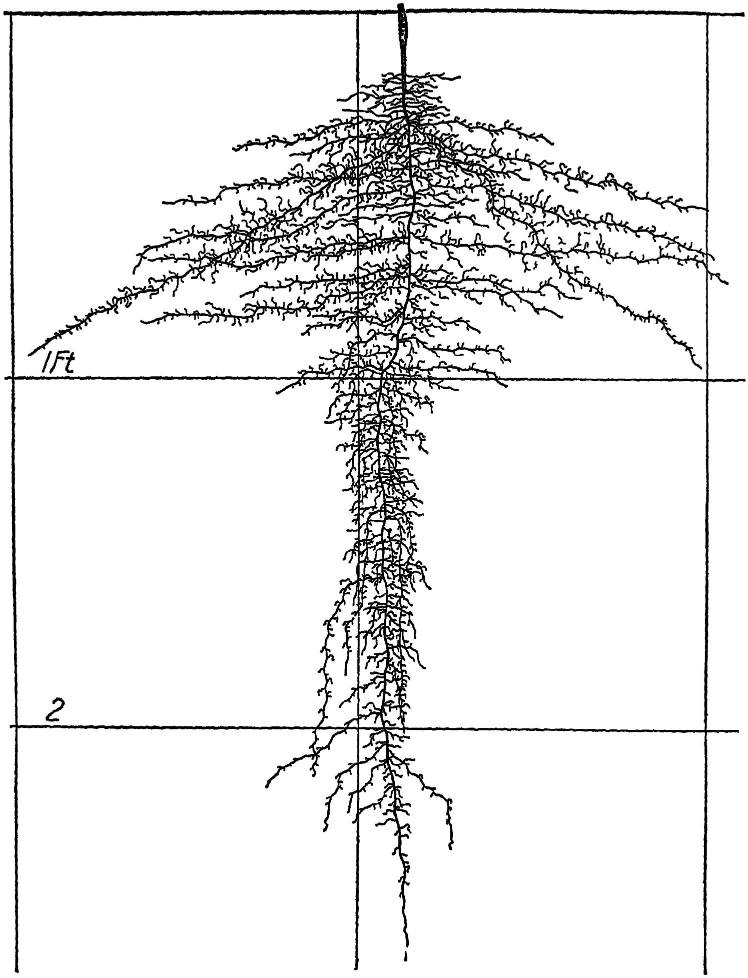


FIG 41 —Taproot system of Purple Top Globe turnip in its early development

were longer and often much more abundant Where they exceeded 1 inch in length, branches of the third order were found at the rate of three to five per inch Thus an extensive absorbing surface was already developed

Midsummer Growth —On July 27, a second examination was made The tops were 1 foot high and each plant had about a dozen leaves At least eight of these averaged 8 by 5 inches in length and width, respectively, although some leaf blades were nearly 1 foot long

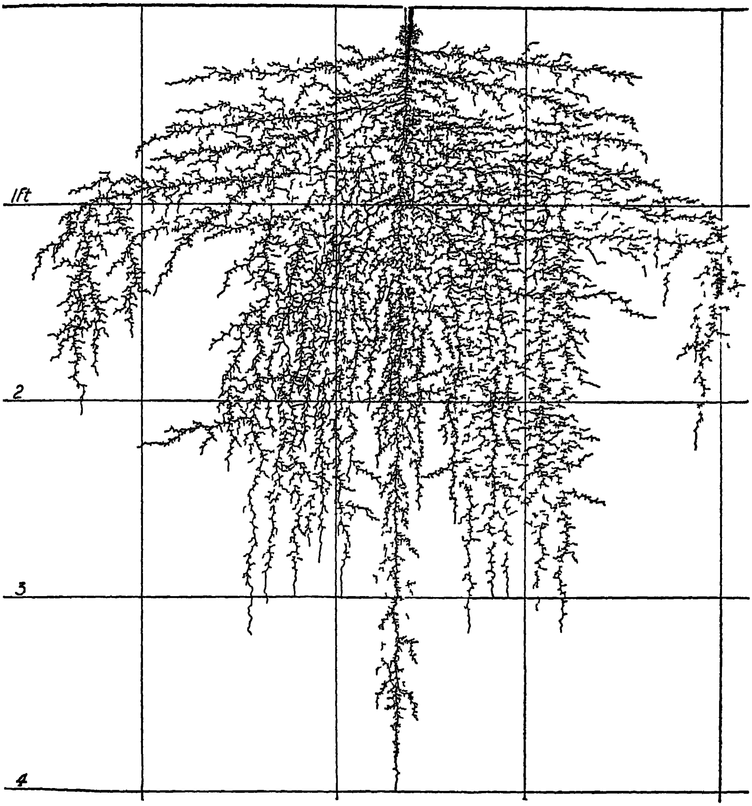


FIG 42 —Root development of turnip on July 27

Correlating with the growth of tops, the roots too had made a marked growth A maximum lateral spread of 2 feet had been attained and many of the taproots reached the 4-foot level Thus the root system nearly doubled in depth and lateral spread (Fig 42) The taproots were now about 0 8 inch thick but usually tapered to 2 millimeters or less at the 6-inch level where they were scarcely larger than many of the major laterals As a result of recent showers, thread-like but very profusely rebranched

laterals filled the surface soil. Although only 1 to 1.5 inches long, they were rebranched to the third order. The number of lateral roots had greatly increased, more than 100 usually being found on the first 12 inches of taproot.

Frequently 12 to 18 major laterals originated at depths of 3 to 10 inches. As before, these ran outward in a generally horizontal direction, some ending at distances of 9 to 18 inches from their origin. But perhaps more frequently they extended outward and then turned rather vertically downward, frequently reaching the 3-foot level. Still others, especially those originating between 6 and 14 inches, ran obliquely outward and downward thus occupying the soil nearer to the taproot.

Below 14 inches few long branches arose from the taproot, but it was clothed with an abundance of short roots (0.5 to 4 inches long) which usually occurred at the rate of about 10 per inch. Branches on all of the laterals were abundant, 8 to 12 per inch were common and sometimes there were as many as 15 to 20. Many were hairlike, others were larger and 2 to 18 inches long. They extended in all directions and gave rise to sublaterals which were often 3 to 5 inches long and themselves rebranched. In fact the network of rootlets was frequently so dense as to form brush-like mats which thoroughly ramified the soil for water and nutrients.

The difficulty of the roots in penetrating the stiff subsoil was shown by the characteristic and abrupt kinks and turns and often zigzag course of the taproots and by both large and small laterals. A study of Fig. 42 gives a fair conception of the thorough occupancy of the soil by the turnip root to the working level at 3 feet. The turnip taste was noted even in the youngest rootlets.

Mature Plants.—A final investigation was made Oct. 5. The plants were practically mature. They had a height of 8 to 10 inches, a spread of tops of 15 inches, and 10 to 12 leaves each. The leaves averaged 13 inches long and 5 inches in width, thus presenting a very large area.

The fleshy portions of the roots were not well developed, the greatest diameter being only 3 inches and the long axis about 4 inches. Rootlets arose from the lower half of the "turnip" in two opposite rows. The larger rootlets were never very abundant. Only 3 or 4 per plant exceeded 1 millimeter in diameter, and these were only 6 to 8 inches long but densely branched to the third order. The rest constituted little tufts of hairlike roots, often 5

to 10 arising in a cluster at the rate of 5 to 10 clusters per inch These were so densely branched and rebranched as to constitute a root network in the soil Below the enlarged fleshy part, the taproot tapered to only 0 5 inch in diameter at the 12-inch soil level

A maximum depth of 5 5 feet was ascertained for several plants Not infrequently the taproots divided in the hard subsoil at depths of 3 to 4 feet into two to four strong branches These often spread a few inches and then pursued more or less parallel but tortuous downward courses The newer and deeper portions of the taproot, which had grown since the July examination, were very profusely branched They were quite similar to the portion in the second and third foot of soil at that examination (Fig 42), although the branches were somewhat longer The origin of the white or slightly yellowish laterals from two rows on opposite sides of the main root was very characteristic throughout

Briefly, the chief developments of the root system since the last examination were as follows The numerous laterals from the shallower portion of the greatly enlarged taproot and its more superficial, horizontal branches quite filled the surface soil The lateral spread had reached a distance of 2 to 2 5 feet on all sides of the plants The marked growth of the taproot into the deeper soil had been accompanied by a similar growth of many of the vertically descending, major branches Thus the soil all about the plant was thoroughly occupied by a dense network of roots to the working level at about 5 feet The degree of branching was even greater than before, even the deeper soil (below 3 feet) was literally filled with cobwebby networks of delicate rootlets, the ultimate branchlets of which were exceedingly numerous Thus the turnip had developed a wonderfully efficient absorbing system

Root Development the Second Season —The root development of the Purple Top Globe turnip at the time of flowering was studied at Norman, Okla Plants were grown in rows 3 5 feet apart The seed was planted about midsummer and root studies made May 1 of the following season Early in March the plants were thinned to 2 feet apart in the rows Earlier investigations had shown that new root growth had started and was well under way by Mar 9, synchronously with the new growth of tops This consisted of an abundance of young rootlets 0 2 to 1 inch in length originating from the taproot and the older portions of its major branches Moreover, it was found that practically the entire root

system had survived the winter, the soil moisture being very favorable and soil temperatures not extremely low (p 19)

On May 1 the plants had just completed flowering The death of most of the basal leaves and the smaller size of the cauline ones had greatly reduced the transpiring area The latter, however, were quite abundant on the 10 to 17 strong branches per plant A rapid deterioration and death of the plants after seeding was observed

The strong taproots pursued a very tortuous downward course to depths of nearly 4 feet In the first foot of moist, fertile soil 58 branches 0 5 to 1 5 millimeters in diameter originated These ran horizontally outward 20 to 41 inches and ended in the surface 12 to 16 inches of soil without turning downward Six other branches were traced outward and downward, their courses being somewhat parallel to that of the taproot In addition, there were exceedingly numerous small branches arising from the taproot and the fleshy portions of the major laterals These varied from 800 to over 2,000 in number depending upon the size of the root and the number of larger branches They were fewer where larger branches were more numerous Approximately one-third of these were 9 to 18 inches long, the others were shorter Most of them had appeared since the March examination when only 200 to 500 roots of this type were found Although some were simple, they were usually well branched

Branching on the major laterals was profuse A rate of 15 to 24 thread-like branches per inch was not uncommon Some of these were 9 inches long and profusely rebranched In places as many as 86 rootlets 1 to 3 inches long were found on a single inch of main root In general, the laterals pursued a path at right angles to the root from which they arose

In the second foot of soil a total of 15 larger laterals 8 to 24 inches in length occurred There were in addition 12 to 20 smaller roots on each inch of the taproot The larger ones, in the first foot of their course, gave rise to 1 or 2 major branches 12 to 15 inches long, and 6 to 15 smaller ones 0 5 to 3 inches long Branching in the third foot of soil was only slightly less pronounced, several strong laterals originating at this level Even in the fourth foot well-branched and rather numerous root termini were found The larger, longer laterals and their greater abundance is believed to be due to the sandier nature of the soil here than at Lincoln

As a whole the roots of the turnip form an extremely intricate network and thoroughly ramify the soil, rather completely exhausting it of its supply of water The older roots were yellowish in color, the younger ones and the root ends were white

Summary —The turnip has a pronounced taproot which elongates at the rate of 1 2 inches per day during the first few weeks of growth In the surface foot of soil most of the branches, few of which are near the soil surface, extend horizontally but those originating at greater depths very early show a tendency to turn downward Plants only 3 weeks old have taproots over 2 feet in length from which an extensive and profusely branched absorbing system is soon developed Forty-day-old plants extend their taproots to the 4-foot level Lateral spread in the surface foot reaches 2 feet, but the surface 4 inches of soil is poorly occupied Thus in a period of 17 days the depth and lateral spread of roots have been nearly doubled By a turning downward of the horizontal roots and a marked growth of more oblique ones, all of which originate in the surface foot, the second and third foot of soil are also exceedingly well occupied Short branches form a dense absorbing network along the path of the taproot Mature plants are rooted 5 5 feet deep and have a lateral root spread of 2 to 2 5 feet By vigorous growth of the numerous vertically descending major branches, the working level has been extended to 5 feet Thus a soil volume of 100 cubic feet is thoroughly ramified (but in the surface 3 inches near the plant only) with an extremely extensive and delicate system of ultimate, absorbing rootlets

In more sandy soil and during a second year of growth the same variety reaches a depth of about 4 feet, develops an extensive, absorbing network in the surface soil, and has a more horizontal spread of branches throughout Moreover, the secondary branches are much longer and ultimate branches far more numerous

Other Investigations on Turnip.—The following observations were made at Geneva, N Y

The roots of a plant of the Purple Top Globe turnip were washed out Oct 29 The root weighed 3 pounds and the foliage was very vigorous, but the scanty root development was a matter of surprise The deepest root appeared to extend no more than 18 inches and the longest horizontal roots reached no further The taproot tapered rapidly from the bottom of the bulb for a distance of 6 inches, where it

divided into two branches, each about $\frac{1}{16}$ inch in diameter Only 13 branches left the taproot that were as thick as a cambric needle, and but few smaller ones These branch roots did not subdivide as rapidly as in most other plants examined [44]

Washing the clayey subsoil, such as occurred here, from roots as delicate as those of the turnip, would not enable one to gain an accurate idea of their full extent This probably accounts in part for these findings

Root Development in Relation to Cultural Practice —A study of the very extensive root system with its extremely delicate network of ultimate branchlets explains why turnips thrive best in a deep, rich, moist loam soil and why the soil should be kept in excellent tilth As with other root crops, such as carrots, beets, and parsnips, a soil that is easily moved by the enlarging fleshy portion of the root is essential, otherwise the roots are very likely to be misshapen and irregular in growth Heavy clay, for example, crusts of which sometimes form after rains and pinch off the plants, not only increases the difficulty of securing a stand, but root penetration is hindered Root crops are removed from such soil with considerable difficulty

The effect of soil environment, as it may be modified by the grower, on the growth of roots of vegetable crops deserves much more study For example, the effect of phosphates in promoting root growth in length and number of branches has long been recognized in agricultural practice They stimulate root development in the early stages of plant growth, and under some conditions are used in large quantities in the growth of turnips and rutabagas

> Dressings of phosphates are particularly valuable whenever greater root development is required than the soil conditions normally bring about Phosphates are needed also for shallow-rooted crops with a short period of growth Further, they are beneficial wherever drought is likely to set in because they induce the young roots to penetrate rapidly into the moister layers of the soil below the surface [127]

It would seem reasonable to conclude that the larger the feeding surface at the disposal of the roots the less exhaustive is the crop on the soil, since the food materials would not be gathered from the surface area only Nitrates, on the other hand, when added to the surface layers of soil, stimulate the production of masses of shallow roots and tend to inhibit root elongation This

would appear to be detrimental to normal crop growth in regions where these layers have very little or no available water during periods of drought, since under these conditions the roots cease to absorb and may die

The usual spacing of turnips in rows 10 to 18 inches apart and thinning to 6 or even 12 inches in the row result in very considerable root overlapping and underground competition Shallow tillage conserves the supply of water without root injury and enables the roots to absorb in the surface layer of soil which is usually the richest in nutrients The large yields often afforded by turnips (600 or more bushels per acre) are produced during only a few weeks of growth Thus the root system must absorb vigorously to supply water and nutrients to this end

CHAPTER XV

RUTABAGA

The rutabaga or Swedish turnip (*Brassica napobrassica*) is very closely allied to the common turnip Both are members of the mustard family and belong to the same genus One may rather easily distinguish it from the turnip, however, by the short stem or neck at the upper portion of the enlarged stem-root vegetable It is a smooth-leaved biennial producing a flower stalk 2 to 3 feet tall Like the turnip it is a cool-season crop but, since it requires more time to mature, it is sown 4 to 6 weeks earlier than the fall crop of turnips

Seed of the American Purple Top variety was planted June 16 in rows 16 inches apart Later the plants were thinned to a distance of 5 inches in the row

Early Development—On July 10 the plants had four large leaves each in addition to about two young ones Leaves of average size had blades 2 5 inches long by 2 inches in width The plants had a height of 4 5 inches

Rutabaga is characterized by a taproot, which was at this stage about 3 millimeters in diameter at the soil surface It tapered to 0 5 millimeter in thickness at a depth of 10 inches Several roots were traced throughout their rather vertically downward course to their ends at depths of 17 to 21 inches No branches appeared in the first inch of soil but on a typical plant 19 arose from the second inch, 11 from the third, and 9 from the fourth At greater depths branches arose at the rate of four to nine per inch Figure 43 shows the somewhat conical shape of the root system The longest laterals originated at about the 3-inch level and ran outward but only slightly downward giving the root system a total lateral spread of 12 inches Most of the laterals, however, did not exceed 2 to 8 inches in length and beyond a depth of 9 inches they were only 1 inch or less long Branching, in general, occurred at the rate of three to eight branchlets per inch Usually these were only 0 1 to 1 inch in length None except the longest had sublaterals

Later Development.—Seventeen days later, July 27, a further examination was made The plants were now 12 inches tall Each had, on an average, six large leaves with blades about 8 inches long and 5 inches wide In addition two smaller ones added to the rather large and constantly increasing transpiring area

The absorbing organs, however, had kept pace in growth with the tops The taproots had extended downward to depths of

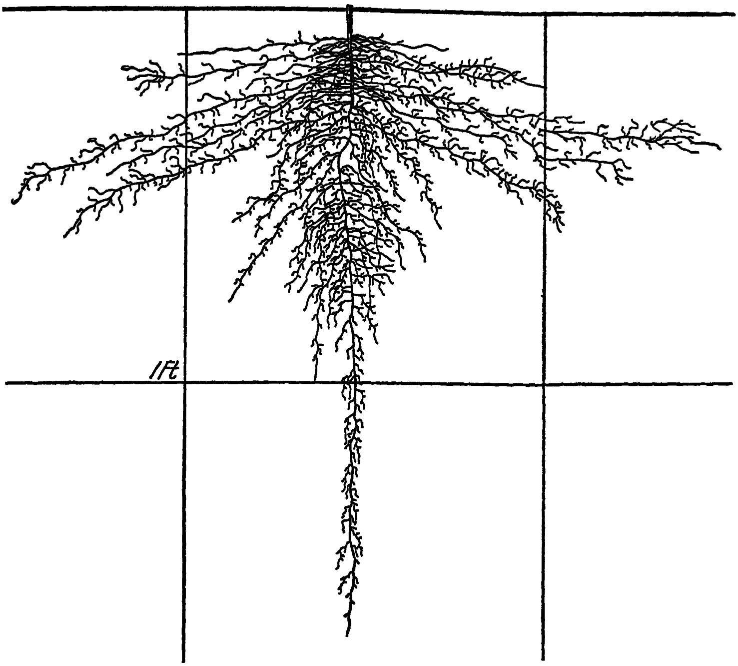


FIG 43 —Root habit of American Purple Top rutabaga at the age of 24 days

about 3 feet The laterals, in their obliquely outward and downward course, increased the lateral spread to 18 inches Many of the larger ones had turned downward at various distances from the taproot and, paralleling its course, extended to near and even beyond the 2-foot level (Fig 44) The enlarged portion of the taproots had reached a diameter of 10 to 15 millimeters near the ground line but tapered to only 2 to 3 millimeters in thickness at depths of 3 to 4 inches Below 10 inches the taproot never exceeded 1 millimeter in thickness and was usually much less

As at the former examination, no branches occurred in the first inch of soil, but frequently 45 to 50 hairlike but densely rebranched laterals were found in two rows, one on each side of the root, in the second inch These were only 0 5 inch or less in length At greater depths the number of branches was approxi-

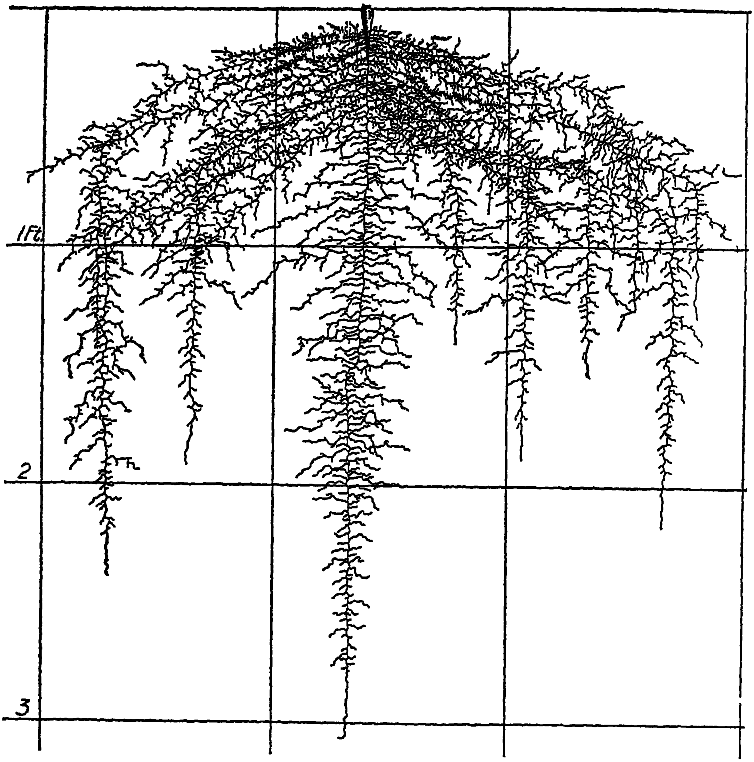


Fig 44 —Rutabaga 17 days older than that shown in Fig 43 Note the widely spreading and vertically descending branches Later these thoroughly ramify the deeper soil

mately as before but the branches were larger and longer Practically all of the long branches, i e, 9 inches or more in length, arose in the first 8 to 10 inches of soil Running outward and then downward they filled in the soil volume not occupied by the main root and its branches and thus greatly extended the territory for absorption (Fig 44) Thus the surface 18 inches of soil was well occupied with roots and some extended

deeper Branching was quite profuse, especially near the taproot where 15 to 20 laterals per inch often occurred Otherwise their former rate of branching (3 to 8 per inch) prevailed The branches, however, were much longer than before, being 0 2 to 3 inches in length, and all of the larger ones were clothed with laterals of the third order This added greatly to the absorbing area

Between depths of 10 and 24 inches the taproot gave rise to six to eight laterals per inch ranging in length from 0 3 to 3 inches Only the longer ones were rebranched Beyond 2 feet the laterals were shorter (0 3 to 1 inch) and somewhat less numerous The last 2 inches of root ends were unbranched

Maturing Plants—By Sept 5 the plants were approximately 2 feet tall Each had about 15 large leaves with blades 12 to 15 inches long and 6 to 8 inches wide The tops had a total spread of about 2 feet

The lateral spread of roots had not increased beyond that of the preceding examination (about 18 inches) In fact most of the major laterals, which originated in the surface 8 to 10 inches of soil, ran obliquely outward only 4 to 12 inches before turning downward Aside from the growth of the taproots, which had doubled in length and reached the 6-foot level (maximum, 75 inches), the main extension of the root system was due to the downward penetration of these large laterals These strong roots varied from 5 to 12 millimeters in diameter and reached depths nearly or quite as great as the taproot

The fleshy portion of the taproot was about 3 inches thick, tapering to 1 inch in diameter at a depth of 4 inches It ran in a generally vertically downward direction but deviated from this course through short distances in penetrating the hard soil Below 3 feet they were often only 1 millimeter in diameter

From irregular areas on two sides of the fleshy part of the taproot, many fine roots arose Although very variable in extent, it was not unusual for these areas to cover a portion of the root exterior 2 to 3 inches long and 1 to 2 inches wide These roots were very much like those on the sugar beet They were mostly 1 millimeter or less in diameter and from 2 inches to 2 feet in length With their densely woolly network of branchlets, they formed great masses of rootlets As many as 80 were counted on a single square inch although where the roots were somewhat larger the number was not so great

A typical root system had 30 major roots, arising in the first foot of soil These were intermingled with smaller branches Many were more than 1 millimeter in diameter and ran outward and downward in such a manner that the soil, 12 to 18 inches on all sides of the plant, was filled with a great network of roots to a depth of 5 feet at least The degree of branching can scarcely be overstated In the first foot of soil the main laterals were clothed with a dense network of branches at the rate of 40 to 45 per inch All of the branches, with rare exceptions, were thread-like and many were profusely rebranched two or more times

Below the 10-inch level large branches were rare, never more than 2 or 3 being found These almost always ran obliquely outward 3 to 5 inches and then pursued a course downward rather parallel to the taproot Small branches arose at the rate of 10 to 15 per inch although the taproot sometimes ran distances of 2 to 3 inches in hard soil and gave rise to only half a dozen small branches In the mellower soil below 4 feet the roots branched much more profusely Here many of the hairlike laterals were only 8 to 12 inches long and often pursued a course parallel to the taproot Others spread horizontally or obliquely With their exceedingly numerous branches they formed cobwebby networks in the moist, mellow soil

An area of 9 square feet formed one end of the volume of soil occupied by the roots of a single plant Of course neighboring plants also extended their roots into this territory From just below the soil surface (an area not occupied at the July examination) to a depth of at least 20 inches, the soil was a veritable network of rootlets At greater depths, until the mellow soil at 4 feet was reached, the root branches were confined largely, but not entirely, to the joints in the clay Here they formed a cobwebby mat of white roots glistening in the dark-colored soil Roots were abundant to the 5-foot level and many extended even deeper Throughout this entire soil volume the root network was of such a pattern that one had to look closely to find the directions of growth of the main roots Thus because of its great extent and high degree of branching the rutabaga has a very efficient root system

Summary—The rutabaga, closely related to the turnip, has a root habit very similar to it The rapid growth of the taproot, the wide spread of laterals in the surface foot, and the tendency

of those originating deeper to extend more obliquely downward are also characteristic of the turnip As in the case of the turnip also, the 3 inches of surface soil, until late in the life of the plant, are never well occupied The vertically downward growth of the ends of the spreading laterals is also the same Plants 6 weeks old have a lateral spread of 1 5 feet, which is somewhat less than that of the turnip, and rather completely occupy the soil to a depth of 18 inches The soil volume thus delimited is not extended except in depth Mature plants have a working level of 5 feet Branches from the taproot, which penetrate somewhat deeper, though abundant, are not extensive, and the bulk of the absorbing system is formed by the numerous long laterals which originate in the 8 inches of surface soil In addition, a dense absorbing network of late origin grows near the plant in the soil surface Throughout the entire extent of the very elaborate root system absorbing masses of rootlets occur in such profusion that their number can scarcely be over-estimated

The root relations in regard to cultural practice discussed under the turnip also apply to the rutabaga

CHAPTER XVI

HORSE-RADISH

Horse-radish (*Armoracia rusticana*) is a coarse, hardy perennial with clusters of large leaves somewhat similar to those of the dock. The flower stalks are 2 to 3 feet tall. It is a member of the mustard family. The plants are grown for their roots which are grated or shredded and used as a condiment. A few clumps are found in nearly every home garden where the plants are allowed to grow from year to year and the roots are dug when needed. In commercial gardens it is grown as an annual crop, the plants being propagated from cuttings of the small side roots.

Mature Plants.—Vigorously growing horse-radish plants were excavated at Lincoln, Neb., in October. The plants were old, formed large clumps, and had grown undisturbed at least 10 years. The soil was a moderately rich, mellow silt loam grading into a well-drained loessoid subsoil.

The plants were characterized by large fleshy taproots which penetrated deeply but were not widely spreading in their habit of growth. The great clumps of leaves were found to arise from two to several separate stalks which, although quite distinct 1 or 2 inches below the soil surface, were attached to the same root. After several plants had been excavated, a typical specimen was selected for detailed description and drawing.

This plant had a crown consisting of five distinct parts as is shown in Fig. 45. The main roots below the crown frequently reached a diameter of 2 inches. The maximum spread of laterals from these roots in the surface foot of soil was 30 inches. Although the average diameter of the soil column occupied by the roots was only about 3 feet, the root system penetrated so deeply that the soil volume ramified by the roots was really very large. Frequently it exceeded 125 cubic feet.

Many fine horizontal roots 1 to 12 inches in length arose in the surface soil. Intermingled with these smaller roots were found several roots 1 to 5 millimeters in diameter. They ranged in

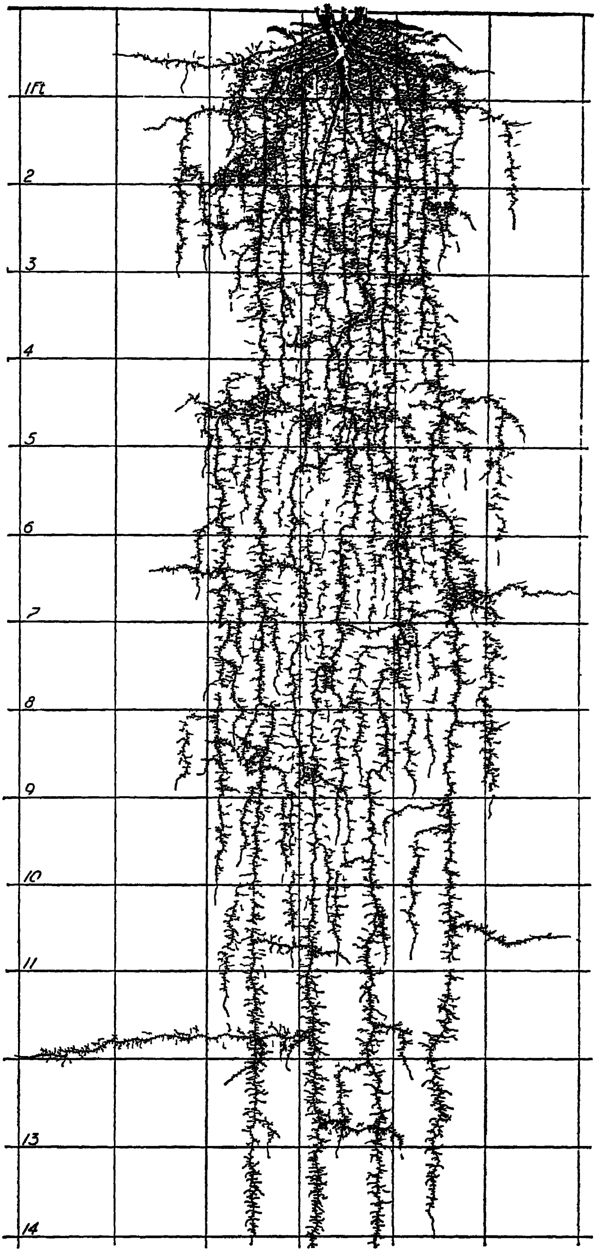


FIG 45 —Mature root system of a 10-year-old plant of horse-radish

length from 1 to 3 feet The larger of these roots turned downward at a distance of 1 foot or less from the base of the plant, the smaller ones usually pursued a more horizontal course

The main root divided at a depth of 6 to 12 inches into six strong branches, thus reducing the taproot to a diameter of only a few millimeters In fact it was not as large as some of the main branches, nor did it penetrate so deeply, ending at the 11-foot soil level The main branches, which were 0 4 to 1 inch in diameter, ran either obliquely downward or outward 3 to 12 inches and then downward Beyond a depth of 1 to 1 5 feet they pursued a generally vertically downward course, although often curving and turning in the characteristic manner shown in Fig 45 As regards size and appearance, as well as manner of branching, the taproot and the stronger laterals were very similar

The larger branches of the major roots were fine and numerous and may be grouped either as horizontal or vertical, although rootlets pursuing intermediate directions were not infrequent Many of the horizontal branches turned downward after pursuing their outward course for a few inches At levels of 6 to 12 feet, where the soil was quite moist, laterals were often found which ran horizontally throughout their entire course The horizontal laterals were rather uniformly 0 7 to 1 3 millimeters in diameter but varied from a few inches to more than 3 feet in length They occurred irregularly In the soil above the 6-foot level these larger horizontal branches arose at the rate of one on each inch or two of the main root Below 6 feet they were sometimes separated by distances of 12 to 24 inches Although 30 to 40 inches was the usual length of these branches, a maximum lateral spread of 42 inches was found at a depth of 12 feet Long laterals, however, were not common at this depth At the 4 5-foot level a layer of hard, lime concretions was found in the soil Here branches were very abundant Not infrequently 4 or 5, approximately 1 millimeter in diameter, occurred on only 1 to 2 inches of the main roots They grew outward a short distance and then turned downward

More or less vertical major branches of the main roots occurred with less frequency They were found on all of the main roots, however These branches usually followed the same course as the main root and not infrequently twined about it, becoming tightly pressed against it as they increased in size This phenomenon is not shown in the drawing

The main roots were well covered with fine, absorbing laterals. Their course, as already indicated, was rather tortuous at least to a depth of 9 feet. Here the soil was continuously moist and much more easily penetrated, and the roots responded by pursuing a straighter, downward path. A maximum depth of 15 feet was attained.

The smaller laterals on both the main roots and their major branches were very fine and usually simple, although some were branched. They did not exceed 0.1 to 0.3 millimeter in diameter. Although somewhat irregular in occurrence, they were always abundant, frequently 16 to 24 being found on each inch of main root. In the first 3 feet of soil this number was often exceeded. Here it was not unusual for the branches to occur in clusters of 2 or 3. The number of laterals on the small branches and on the main roots at depths greater than about 6 feet was 16 or less per inch. These absorbing roots were frequently 3 to 4 inches in length in the first 8 feet of soil. But the root length rather gradually decreased from the surface-soil layers to within a few inches of the root tips where rootlets had not yet formed. At a depth of 12 feet they averaged only about 1 inch in length. Branches were also shorter on the smaller laterals. The roots were white in color and could be easily identified at any depth by their characteristic taste.

Summary.—Horse-radish is a perennial with a very thick, fleshy taproot system which penetrates to depths of 10 to 14 feet but does not spread widely. The taproot gives rise to many fleshy laterals in the surface foot of soil, where also frequently the main root divides into several rather equally prominent branches. These penetrate more or less vertically downward, or, more usually, first run obliquely outward 4 to 12 inches and then pursue their very tortuous downward course. A diameter of 4 millimeters is often retained even at a depth of 6 feet. Supplemented in the surface soil by numerous fine horizontal roots and profusely branched throughout, the main roots ramify a very large soil volume. The larger of the fine laterals are usually either horizontal or vertical in direction of growth and are from a few inches to over 3 feet in length. Their distribution is somewhat irregular. Smaller branches are numerous. Thus the absorbing system as a whole is both extensive and profuse.

Root Habit in Relation to Cultural Practice.—The great extent and rapid development of the horse-radish roots explain why the

plants grow best in a very deep, moist, fertile loam soil, why deep plowing is beneficial, and why a good soil structure is an important environmental factor for growth Soils for vegetables should always be deep A depth of 8 to 12 inches is desirable for most soils But if they are shallow, they should be deepened gradually and not all at one plowing or in a single year Too much subsoil brought to the surface at once is usually not beneficial In planting the roots, they are placed with the upper end of the cutting 2 to 5 inches below the soil surface The soil should be packed firmly about them to insure good contact and resultant prompt growth Weeds should be kept out by thorough cultivation so that sufficient water and nutrients will be available late in the season when the plants make their best growth On hard, dry, or shallow soil the roots are very likely to be crooked, unshapely, and scarcely fit for use The growth of long, straight roots of more uniform size is promoted by preparing and maintaining a deep, mellow soil To aid in securing shapely roots

> some growers remove the side roots early in the season This is done by removing the soil and stripping the side roots from the upper part of the main root The soil is then replaced This treatment results in the production of large, compact roots, but unless the work is carefully done, serious injury may follow The earlier in the season the trimming is done the less check there is to growth [155]

Since plants several years old have a lateral spread of roots scarcely exceeding 18 inches, it would seem that the usual spacing for plants grown a single year is sufficiently great to allow a good root development The usual distance is 10 to 18 inches in rows 3 to 4 feet apart If allowed to grow more than 1 year, the roots are apt to become hollow and undesirable for market.

CHAPTER XVII

RADISH

The radish (*Raphanus sativus*) is one of the commonest of garden vegetables, being especially in favor with the home gardener because of the ease and rapidity with which an early spring crop may be obtained If planted early, it forms seed and completes its life cycle in a single season Varieties planted later set seed during the second season of growth The branched flower stalks are 1 to 3 feet in height The plants are grown for their pungently flavored roots, including the upper portion of this swollen, edible part which is morphologically a stem The "roots" vary much in size and shape from those that are short and globular, through conical and oblong, to the spindle-shaped type

EARLY SCARLET TURNIP WHITE-TIPPED RADISH

Seed of the Early Scarlet Turnip White-tipped radish was planted Apr 10 The rows were 14 inches distant and the plants thinned to 2 inches and later to 4 inches apart in the row

Early Development—Radish seeds germinate and produce a taproot system in a remarkably short time They have been observed to form six to eight laterals on the upper inch of the taproot only 4 days after planting and at a time when the cotyledons were just unfolding Nine days later, when the plumule was appearing, secondary laterals had been formed This shows that a plant needs an efficient absorbing system before much leaf area is exposed to the dry air

On May 18 the plants each had about five leaves and other leaves were just appearing The average leaf surface was 22 square inches The total spread of tops was about 6 inches

The fleshy portion of the strong taproot was 1 to 1 5 inches in diameter The taproot pursued a nearly vertically downward course, curving laterally through short distances An average depth of 19 inches and a maximum penetration of 22 inches were reached The diameter of 2 5 millimeters, found just beneath the enlarged portion of the taproot, decreased at a depth of 6

inches to only 1 millimeter, a thickness that was maintained throughout the course of the root Just below the enlarged part of the taproot, or at most only a few millimeters below, numerous branches arose (Fig 46) These extended outward in a generally horizontal direction but often curved upward or downward The longest reached a distance of 12 inches from the base of the plant, but most of the roots were only 2 5 to 3 inches in length

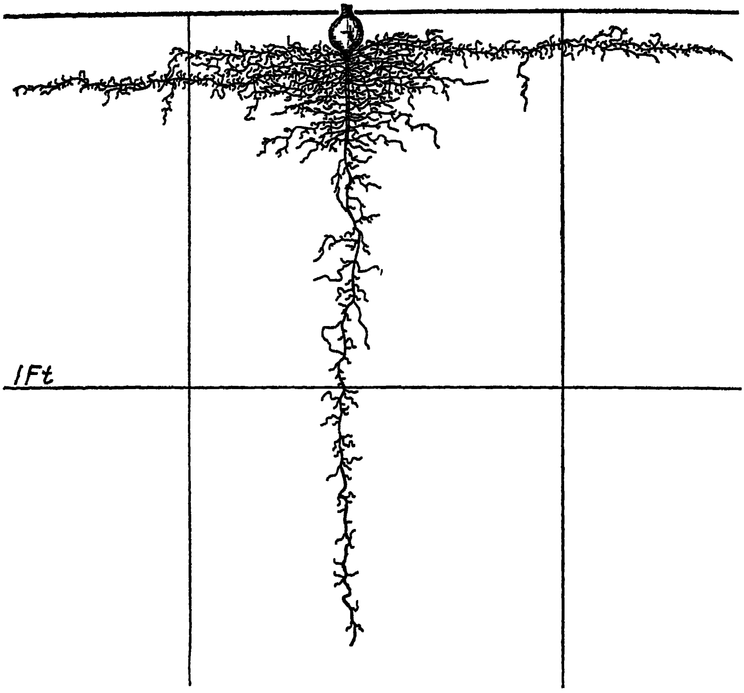


FIG 46—Root system of the Early Scarlet Turnip White-tipped radish about 5 weeks old

Laterals were thickest on the first 3 inches of the taproot, where they occurred often in groups of twos or threes, in two more or less distinct rows on opposite sides of the taproot From 40 to 45 roots often sprang from the first 3 inches of the slender portion of the taproot Below this they were fewer, shorter, and more poorly branched or entirely destitute of laterals They spread horizontally on all sides of the plants Branching was very profuse Laterals of the first order occurred at the rate of 5 to 20 per inch and varied from 1 millimeter to 2 inches in length.

Although branches of the second order were found but rarely, the thread-like roots of these young plants thoroughly ramified the surface layer of soil

Effect of Soil Structure on Root Development.—Radishes were grown in rectangular containers with a capacity of 2 cubic feet and a cross-sectional area of 1 square foot A rich, sandy loam soil of optimum water content was screened and thus well aerated One container was filled with soil with very slight compacting It held 173 pounds Into the second container, 232 pounds of the soil were compacted Surface evaporation was reduced by means of a thin sand mulch When the plants were 3 weeks old and five or six leaves had developed, the side of each container was cut away and the root system examined The taproots had reached a maximum depth of 22 inches in the loose but only 5 to 8 inches in the compact soil The laterals in the first 2 inches of dense soil were more numerous, of somewhat greater diameter, and slightly longer (maximum 6 5 inches) They were also much more branched But in the loose soil branching occurred throughout to near the root tip That roots of many species penetrate more deeply in loose than in compact soils and that under the latter condition branching is increased has been shown by numerous investigations[87,163 48,69 2]

Two-months-old Plants—A second examination was made June 11 The plants now had stems nearly 2 feet tall with 9 to 11 branches They were flowering abundantly A few of the oldest leaves had turned yellow and dried The cauline leaves were relatively smaller than the basal ones Plants of average size had leaf surfaces slightly less than 3 square feet in extent

At this time the fleshy portion of the root was about 2 5 inches thick On about half the plants a second storage reservoir was being formed below the first, or at least the root was considerably thickened The strong taproot, about 4 millimeters thick throughout the first 8 inches, which was the most branched part of its course, ran quite vertically downward to a depth of 3 feet The root ends were not thick as at the preceding examination but greatly attenuated and quite free from branches for distances of 5 to 7 inches In fact below 10 inches branching was relatively sparse although greatly promoted where the roots entered earthworm burrows or soil areas enriched by the presence of former roots Here they sometimes coiled about and branched much more profusely (Fig 47).

A remarkable degree of branching occurred between the depths of 2 and 8 inches In one representative plant 49 laterals arose from the first inch of taproot below the enlarged part, 34 from the second inch, 20 from the third, and 11 to 15 from each of the next

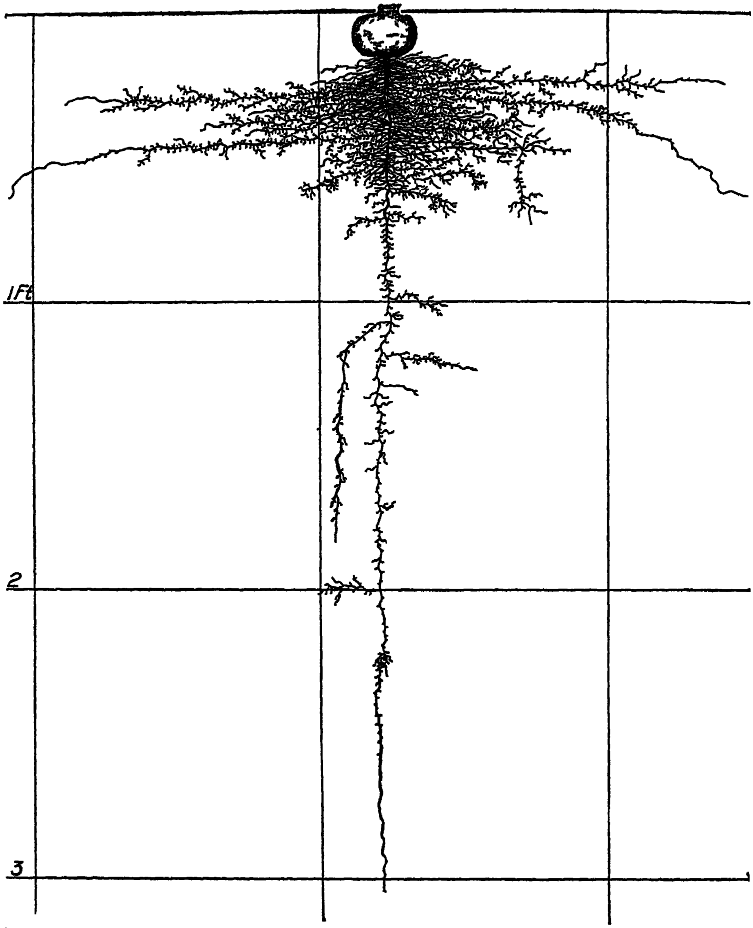


FIG 47—Characteristic root habit of a 2-months-old radish Most of the fibrous roots are distributed in the surface soil

3 inches, respectively Below this, in the first foot, the taproot branched at the rate of 5 to 7 laterals per inch Many of the branches arose in groups of twos or threes from two rows on opposite sides of the root They usually extended horizontally in all

directions from the taproot. Many were only 2 to 4 inches long, some reached distances of 13 to 17 inches from the base of the plant. That they, like the taproot, were growing rapidly was clearly indicated by the long, unbranched root ends. The laterals were well furnished with branches which occurred at the rate of 4 to 10 per inch. Although many of these were very short (0.2 inch or less), others reached a length of 1 to 3 inches. Most of the older ones were rebranched with short laterals and branches of the third order were frequent. The thread-like character of the branches and the great network of delicate branchlets are very characteristic of the radish and make it quite difficult to excavate.

Mature Plants.—A final examination was made July 13 when the plants were 26 inches tall and in the flowering stage. The vigorous plants had 18 to 22 leaves, usually with a flower stalk in the axil of each. The large transpiring surface (nearly 5 square feet) may be visualized when it is recalled that the larger leaves were 8 to 12 inches long and 4 to 6 inches in width.

Just below the soil surface the enlarged globular portions of the fleshy taproots were 2.5 to 4 inches in diameter. Although usually cracked and fissured, they were still quite firm and well stored with food. Below this portion secondary, irregular enlargements occurred on practically all of the many plants examined. These varied from 0.5 inch to over 2 inches in diameter, the taproot frequently being swollen for a distance of 6 to 8 inches (Fig. 48).

Even a casual inspection of Fig. 48 shows the marked growth the roots had made since the examination a month earlier. The taproots frequently reached depths of 6 to 7 feet, and a maximum penetration of 7.2 feet was found. The widely spreading, horizontal lateral branches had extended the absorbing area to over 3 feet on all sides of the plant. A maximum lateral spread of 4.1 feet was ascertained. Not only was the surface soil from 3 to 12 inches thoroughly ramified over a wide area but also the deeper soil, even beyond 4 feet, was penetrated by strong, well-branched lateral roots.

The taproots pursued a generally vertically downward path but with characteristic kinks and curves as indicated in the drawing. Throughout their course in the surface 4 to 12 inches of soil they were so covered with branches, both large and small, that they formed a cobwebby network. Below 12 inches, the

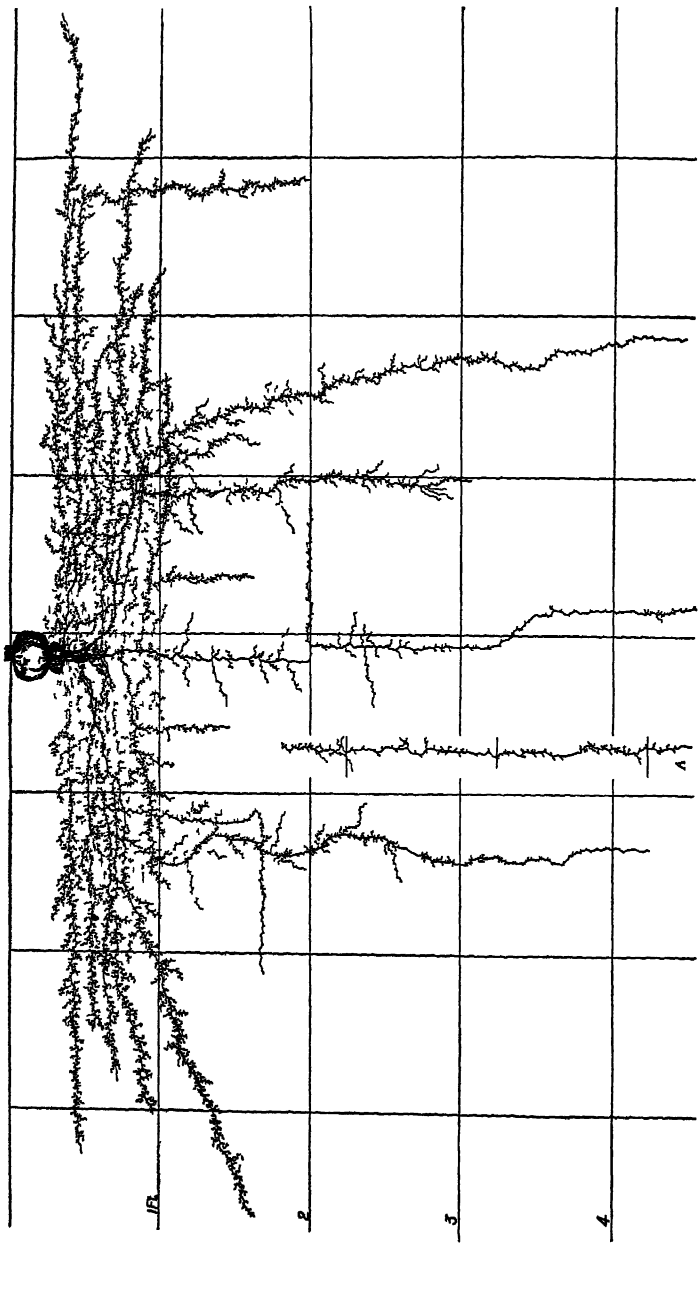


FIG 48—Root system of radish that had formed a flower stalk, excavated July 13 The insert (A) is a continuation of the taproot which reached a depth of more than 7 feet

taproots, now about 2 millimeters in diameter, were very much kinked and curved and sometimes turned abruptly. Large laterals were not abundant, frequently only 5 to 8 occurring below the first foot of soil. These were rather poorly furnished with short branches and seldom exceeded 8 inches in length. Their direction of growth was mostly horizontal. No branches over 1 to 2 inches long occurred at greater depths, but numerous, short branches were found throughout the course of the taproot.

The larger lateral roots, originating in the surface 4 to 12 inches of soil, usually occurred at the rate of six or more per plant. They were 1.5 to 2 millimeters in diameter throughout the first 8 to 12 inches of their course which, as among the very numerous smaller laterals, was characterized by many kinks and turns. Frequently, the main laterals gave rise to branches quite as large as themselves. All branched profusely, frequently to the third and fourth order, especially the older parts. Portions of the laterals were found that had only three to four branches per inch or, indeed, were destitute of them, they were typically clothed with rootlets 0.4 to 1 inch long at the rate of 8 to 12 per inch.

As a whole the root system of the radish is rather clearly differentiated into a deeply penetrating portion consisting of the taproot and a few of its widely spreading and deeply penetrating branches and a shallower part which spreads widely but is almost confined to the surface 4 to 12 inches of soil. Here dense masses of delicate, cobwebby roots were profuse. This soil layer was so thoroughly exhausted of its water that during drought many of the cobwebby rootlets of the intricately branched network of roots shriveled and died. The absence of roots in the surface few inches of soil is characteristic.

Summary.—The Early Scarlet Turnip White-tipped radish is characterized by a rapidly growing and deeply penetrating taproot. At the time of the removal of the fleshy portion of the root for table use, the root system is not extensive when compared with that of most vegetables. Although it may penetrate to a depth of 2 to 3 feet and have a lateral spread of 12 to 16 inches, most of the absorbing area lies in the surface 2 to 8 inches of soil. Even on fully matured plants only the portion of the taproot lying in the 2 to 12 inches of surface soil gives rise to large laterals. Most of these extend horizontally to distances of 3 feet or more on all sides of the plant. They branch profusely and rather thoroughly fill the surface soil with a network of absorbing

rootlets The deeper soil is ramified by the taproot and by a few of the major roots or their branches which originate in the surface foot The taproot penetrates to depths of 6 to 7 feet The large branches reach depths of 3 to 4 feet and are well clothed with short laterals.

THE EARLY LONG SCARLET RADISH

Seed of the Early Long Scarlet radish was planted at Norman, Okla , Apr 18 Conditions for growth were very favorable both as regards temperature and soil moisture and the plants grew vigorously When 20 days old and at a time when the tops consisted of five to seven leaves, the first root examination was made

Early Development—The taproots, some of which were already 0 5 inch in diameter, had grown at the rate of 1 2 inches per day. They reached a maximum depth of 2 feet Branches were found from just beneath the soil surface to near the root ends They were very abundant, 37 to 53 occurring on the first foot of the taproot alone In length, they ranged from a few millimeters to 15 inches. Their direction of growth was mostly horizontal although below 8 inches a few ran obliquely outward and downward All of the longer ones were branched Branches occurred at the rate of about 4 per inch and many of them were 1 to 2 inches long These also were rebranched The entire root system was covered with root hairs and was apparently functioning vigorously Most of the absorbing surface occurred in the first foot of soil, some of the laterals extending almost to the soil surface But the second foot was also ramified by the taproot, by a few obliquely descending major laterals, and by the rather numerous branches from these The second foot of soil was moist and fairly mellow and was soon to become the seat of vigorous root activity At this time the root system had, in general, the shape of an inverted cone 2 feet long and about 28 inches wide

Later Development.—Twelve days later, May 20, the fleshy portion of the taproot had increased to 1 inch in diameter The roots were enlarged to a depth of about 8 inches Some of the major branches were also fleshy near their origin Marked changes had occurred during the 12-day interval The depth of penetration had increased to 3 feet and the lateral spread to a maximum of 2 feet Although the general shape of the root sys-

tem had not changed, many of the secondary laterals had greatly elongated, the absorbing area was much extended, the second foot was well ramified to a distance of 8 inches on all sides of the taproot, and the third foot was almost as fully occupied as was the second 12 days earlier. Branching throughout was even more abundant. The root system was growing vigorously.

Mature Plants.—The plants continued their rapid growth throughout June and by July 6 they averaged 30 inches in height. The tops spread so widely that they nearly covered the soil, although they had been thinned earlier until the mature plants were 18 to 24 inches apart in rows 3.5 feet distant. Blossoming had ceased and the seed pods were maturing.

The fleshy roots were 3 to 5 inches in diameter and 8 to 14 inches long. The taproots were several millimeters in diameter, however, even to a depth of 3 feet. They pursued a generally downward, although somewhat tortuous, course through the rather compact subsoil and reached depths of 4.5 to 5 feet. Several of the major laterals, originating from the fleshy portion of the root or near its base at depths of 8 to 10 inches, had a lateral spread of 40 inches. Many of these ran far outward and then turning downward penetrated to depths of 2 to 3 feet. Others pursued a horizontal course throughout but gave rise to long, vertically descending branches some of which reached the 4-foot level. Lateral branches on all of the roots were very much longer than formerly, penetrating the soil in all directions for distances of 6 to over 30 inches.

In the process of growth expansion the plants had forced themselves 1 or 2 inches out of the soil. Similar root heaving has been observed on other fleshy rooted plants.[83] This was clearly shown not only by the exposed crown and upper portion of the fleshy root but also by the abrupt inward curving of the main roots originating from the fleshy part of the taproot. Earlier examinations showed this same type of root running horizontally. The phenomenon was very pronounced since numerous curved branches 2 to 10 millimeters thick all turned obliquely downward at their origin. Some of the shallower horizontal roots were actually stripped of their laterals and pulled above the soil surface.

Owing to the very dry soil and perhaps in part to high temperatures, many of the roots in the shallower soil had ceased absorbing, others had died. Very few active roots occurred within a

radius of 2 feet from the base of the plant and to a depth of over 12 inches Thus absorption was confined to the younger parts of the horizontal branches and to those lying deeper in the soil The root system was very extensive, however, both in lateral spread and depth thus ramifying a very large soil volume Throughout this soil mass, except as already indicated, branching was very profuse, great mats of glistening white rootlets filled the soil It is remarkable that a plant in such a short period of growth can produce such an extensive and intricate absorbing system

Summary —The root system of the Early Long Scarlet radish is of an entirely different type from that of the Early Scarlet Turnip White-tipped variety In its early development the vertically penetrating taproot was branched throughout, mostly with horizontal laterals, from the soil surface to near its tip, the root system having the general shape of an inverted cone When the roots have reached the size used for eating, they penetrate to depths of 3 feet and the much-branched laterals spread radially to distances of 2 feet, the conical nature of the root system being in general retained Mature plants are characterized by very fleshy taproots, 4 5 to 5 feet long and many major laterals, all of which arise in the surface foot of soil These spread widely (maximum, 40 inches) and often turn downward near their ends They also give rise to major laterals which penetrate deeply Thus, although the surface soil is well occupied, the subsoil to depths of 3 to 4 feet is also more or less filled with the much-branched lateral rootlets Further investigation may show that these differences in root habit are due in part to varietal characters and in part to soil environment

Other Investigations on Radish —The root systems of the Gray Summer Turnip variety and the London Particular Long Scarlet were washed from the soil at Geneva, N Y

> The roots of both penetrated the soil a distance of 2 feet and the branches extended on either side more than 21 inches, mingling with those from adjoining rows The taproot did not begin to branch much until some distance below the edible part The branches at first were few in number, usually but two or three from the taproot These extended nearly horizontally, and ramified toward their extremities into many fibrous roots The greater part of the feeding roots lay in the upper 8 inches of the soil Though the edible roots of these two varieties are quite different in form, their rooting habits show no difference [43]

Certain German investigators have also observed that the fleshy portion of the main root is practically without branches, that the taproots reach depths of 12 to 20 inches, and that the ultimate branching is very diffuse, branches of the third order being abundant [89]

Steaming the soil has been found to increase the total number, size, and yield of radishes, a fact which is undoubtedly connected with a greater development of the root system (*cf* p 251) [139]

Root Development in Relation to Cultural Practice —Although the radish, like its wild ancestors, will grow in nearly all types of soil, a light, friable, fertile soil is best Since the crop develops very rapidly and the root system, except in plants grown for seed, is not extensive, the most favorable conditions for root activity should be attained by thorough seed-bed preparation and shallow cultivation Stirring the 2 inches of surface soil will not harm the roots, since practically all of them lie deeper They do nearly all of their absorbing in the surface 6 to 8 inches Hence, water should be conserved in this soil layer, manure and fertilizers supplied to it abundantly, and competing weeds kept out so that growth will be rapid and continuous

It is well known that radishes will thrive under close planting or as an intercrop between rows of later-maturing plants A knowledge of the shallow, non-extensive, but well-branched root system helps one to understand why this is the case The ramification of the soil by the roots of older plants and probably by longer-season varieties is quite a different matter Undoubtedly close planting, which results in shading aboveground as well as root competition in the soil, affects the size and development of the fibrous portion of the root system just as it does the edible part The effect of shading on the growth of roots has been clearly demonstrated, for example, in the case of certain tree seedlings

In white-pine seedlings grown in Vermont

> darkness induces the growth of tall seedlings with poorly developed roots, a diffuse light, the growth of shorter plants and longer roots, and the full light produces short stocky plants with long branching roots [20]

For example, seedlings of similar age grown in the nursery under full shade had unbranched taproots 3 5 centimeters long, those grown in half shade were 4 5 centimeters long and had the beginnings of laterals, and seedlings grown in full light had taproots

5.2 centimeters long and a lateral development of roots nearly seven times as great as those in half shade. Among 50 seedlings excavated about 3 weeks later, the length of the root systems were 4.5, 8.2, and 13.8 centimeters and the total number of lateral branches on the lot 5, 143, and 468, respectively.

Plants that are crowded cannot develop efficient root systems and their activities are confined to the shallower soil.[173] Unless this is kept very rich and well moist, drought and reduced yields are inevitable. Since plants with like root systems are making similar demands at the same depth at the same time, they are least fitted to be crowded together. Intercropping and growing mixed cultures more nearly approaches nature's method of producing a dense growth of vegetation. For scientific progress in this direction a thorough understanding of root relations is indispensable.

CHAPTER XVIII

STRAWBERRY

The strawberry (*Fragaria chiloensis*) is an herbaceous perennial The very short, thick stems occur close to the surface of the soil Although not always included among vegetable crops, its wide distribution, the temporary nature of the crop, and its common occurrence in gardens warrant its inclusion here It is the most valuable of the small fruits grown in the United States [150] It is indeed a cosmopolitan plant, growing and thriving under a wide range of conditions The best crops are usually grown in rich, rather moist soil during a cool season

Mature Plants —A strawberry of the Dunlap variety, one of the most important commercially, was studied on an area of silt loam soil about a mile distant from the experimental field in Lincoln The plants were excavated June 24 when blossoming and fruiting were nearly completed They had grown 3 or 4 years in this field

The underground parts are characterized by a dense network of fibrous roots which arise from the much-thickened, short scale-covered stem (Fig 49) Plants of average size possessed about 36 roots, each approximately 1 millimeter in diameter, and about 9 smaller ones These fibrous roots radiated outward or downward in all directions from the horizontal to the vertical Many spread outward somewhat obliquely and turned downward A maximum lateral spread of 12 inches and a maximum depth of 37 inches were ascertained The root system was characterized by a dense network of fibrous roots in the 10 to 12 inches of soil next to the surface In the surface foot, and especially in the upper 6 inches, the roots were rebranched at the rate of 3 to 10 fine rootlets per inch The branches were usually quite kinky and varied from 0 3 to 6 or even up to 10 inches in length The longer ones usually occurred on the older roots The primary branches were rebranched at the rate of 3 to 8 per inch with laterals 0 1 to 1 inch long The longer secondary laterals were again rebranched. Where the main root had been cut or other-

wise injured, 3 to 5 long branches frequently arose from the root tip Such branches usually extended only slightly horizontally but nearly always ran rather directly downward

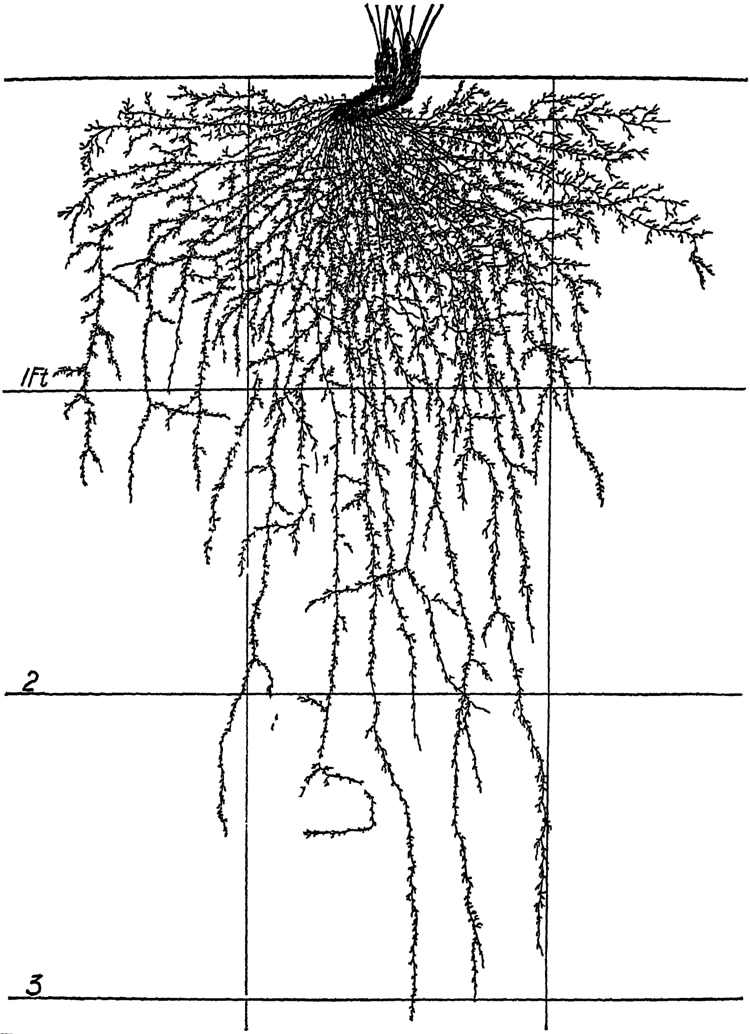


FIG 49 —Underground parts of a 3-year-old Dunlap strawberry excavated in June after blossoming and fruiting

Below the surface foot of soil the rate of branching was somewhat less, usually 3 to 6 rootlets per inch, and the branches were

shorter, although rootlets 3 to 4 inches long were frequently found. The first 2 inches of roots near the stem were branched but little. Occasionally a root 1.5 millimeters in diameter, originating from the rhizome, was more profusely branched than the rest, the dense branching being largely confined to the surface foot of soil.

The young roots are white in color. As they become older, their color changes to a light brown and finally to very dark brown or nearly black. Plants starting from runners have many long, young, light-colored roots.

Summary.—The fibrous root system of the strawberry arises from the short, thick stems near the soil surface. Just beneath the surface horizontal roots extend about 1 foot on all sides of the base of the plant. This delimits the lateral spread. The surface foot of soil is fully ramified by obliquely descending roots as well as many more or less vertically descending ones. The latter, especially, also ramifies the second and some of them the third foot of soil. Branches are mostly short but abundant, usually being more profuse in the surface 12 inches. The root system is relatively shallow and not extensive.

Other Investigations on Strawberries.—A plant of Triomphe de Grand variety of strawberry was washed from the soil at Geneva, N. Y., in midsummer. The horizontal roots were found to be few and short, the longest being traceable only 6 inches. The greater part of the roots extended nearly perpendicularly downward, and nearly all the fibrous roots were found directly beneath the plant. The roots reached a depth of 22 inches. New roots were found growing from the rhizome about 1 inch above the old ones. The longest of these had attained a length of 6 inches. They were white and tipped at their extremities with a thickened point.[42]

Strawberries of the Warfield variety were studied at Madison, Wis. The plants were 3 years old. They were washed from the soil late in May when the fruit was maturing. The roots were contained within a very small soil volume. The deepest roots extended a little less than 2 feet and the horizontal ones reached scarcely beyond the area covered by the leaves. Most of the roots grew downward and all but the merest fraction of them were contained within the first foot of soil. The soil was a light, clay loam which was underlaid at a depth of 1 foot with a subsoil of sandy clay. The soil had been cultivated about 3 inches deep.[45]

It was found at the same station that certain herbaceous plants, including the strawberry, start growth extremely early in spring As early as Mar 22, when the ground was free from frost in places receiving the most insolation, the roots of strawberry had made considerable growth Root growth in spring is most active near the surface of the soil which is first warmed by the sun's rays "Thus the parts of the soil from which roots are in a measure excluded during the dry weather of summer may serve as a feeding ground for them in early spring "[46]

That there is considerable difference in the root habits of varieties is indicated by the statement that some varieties which are usually a failure in dry climates because of their deficient root system are enabled by irrigation to flourish to such a degree as to be among the most profitable [6]

The root system of the wild strawberry (*Fragaria virginiana*) has been examined where the plants were growing in a spruce forest The lateral spread and depth of penetration were very similar to that described and illustrated for the cultivated variety In drier habitats it would undoubtedly be more extensive [167]

Root Habits in Relation to Cultural Practice.—The fact that native strawberries, from which the cultivated varieties have arisen, grow in nearly all types of soil from seashore to mountain top, indicates a wide range of soil and climatic conditions for cultivated plants [19] The rather limited root range of the plant easily explains its well-known susceptibility to drought as well as its ready response to fertilizers It emphasizes the importance of providing irrigation in regions of moderate and fluctuating rainfall if large and regular crops are to be obtained The need of a rather constant water supply about the roots is indicated by the distribution of native strawberries in dry grassland areas Here they are found in the better-watered soils in ravines and along creeks and river bottoms, and often fringe thickets and woodlands Perhaps an ideal soil would be a sandy or gravelly loam underlaid with a pervious clay, *i e*, one retentive of moisture yet easily tilled By proper methods of tillage, mulching, and irrigation much can be done toward furnishing the roots with a constant moisture supply

Soil for strawberries should be thoroughly prepared Deep plowing and thorough pulverizing a considerable time before transplanting encourages the roots to penetrate more deeply, thus lessening the danger from drought and injury from cold

Soil thus prepared will catch and retain more moisture than a poorly and recently plowed soil

In transplanting, only large, sturdy, young plants with a vigorous root system should be selected These plants have thick, turgid, light-colored roots quite in contrast to the dark, less vigorous appearing roots of older ones A plant with a healthy root system and a comparatively small top is much to be preferred to one in which these conditions are reversed The transplants make a

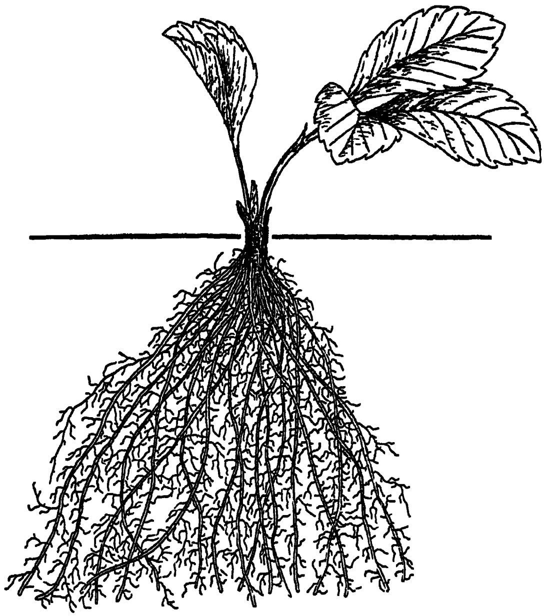


FIG 50 —A strawberry plant correctly pruned and set at the proper depth

better growth if both tops and roots are pruned before setting Very little pruning of the tops will be required if the plants are secured early The roots are frequently cut back to a length of 3 to 5 inches The removal of a portion of the root system permits better spreading of the roots and facilitates transplanting [147]

Great care should be exercised so that the roots do not dry out in the process of transplanting It is also important to spread the roots in the soil and to press the moist soil firmly against them, thus establishing good contact Care should also be taken to set the plants at the proper depth When the roots are too deep and the stem is buried under the soil the crown or terminal bud

will be covered with soil and the plant may not grow Exposing too much of the stem, thus placing the roots too near the surface where they will become dry, is also harmful (Fig 50) The fact that new branches from the perennial stem appear above the older ones explains the tendency for the short stem to become more and more above the soil as the plant becomes older

Because of the method of propagation by rooting aboveground stems (stolons or runners), commercial growers generally prefer the matted-row system of planting since it is the simplest and easiest to maintain Moreover, it almost invariably gives the highest yields [147,114,177] In one experiment 43 varieties were employed The transplants are often set 10 to 30 inches apart in rows 3 to 3 5 feet distant The runners are allowed to form plants 6 to 12 inches on either side of the row thus leaving sufficient space between the rows for cultivation Sometimes the offshoots are spaced 6 to 11 inches apart Under such conditions the roots thoroughly ramify all of the soil and extend a considerable distance between the matted rows In fact all of the space between the rows may be well occupied by roots They are disturbed by cultivation unless it is very shallow Plants in hills or hedge rows often develop more extensively, according to the root and shoot competition imposed upon them, and the fruits are usually larger

Proper cultivation is said to be the most important factor in strawberry production The root system needs thorough aeration and a constant supply of moisture Both of these conditions are attained by preventing the formation of a soil crust due to driving rains or irrigation Keeping the soil mellow also encourages the rooting of the runners Strawberries will not stand competition of weeds, the tops are easily overshadowed and the shallow roots are relatively not extensive It is important, therefore, that cultivation should be thorough and timely but shallow The roots are not exhaustive of soil nutrients Loosening and aerating the soil seems quite as important as manuring it Indeed, the saying "tillage is manure" applies very well to the root system of this plant

Mulching in the fall is an essential practice with such a superficially rooted, perennial crop It not only protects the aboveground parts from sudden temperature changes and drying winds in winter and spring but also tends to prevent the soil from heaving and breaking the roots Moreover, it conserves moisture and

inhibits the growth of weeds By leaving the mulch intact in the spring the soil is kept cool and damp during the season when the fruit is being produced Because of the lower soil temperature, absorption and growth are slower and blossoming is delayed The root relations also explain why a mulch is usually more beneficial in regions of light and precarious snowfall than in those in which a blanket of snow lies on the ground all winter

Among the hundreds of varieties of strawberries grown in the United States there must be considerable variation in rooting habit and adaptability of the root system In selecting, adapting, or breeding varieties for particular regions, the underground parts of the plants should be given consideration

CHAPTER XIX

PEA

The garden pea (*Pisum sativum*) is a hardy, cool-season annual It is quite variable in size, ranging from 1 to 6 feet in height, since some varieties are dwarf, others half dwarf, and still others tall It is cultivated in nearly all home gardens, in market and truck gardens, and is also grown on a very large scale for canning Since it does not thrive during midsummer it is grown as a partial-season crop, *i e*, in spring and early summer in the North and as a winter and spring crop in the South Like other members of its family (*Leguminosae*), through the agency of bacteria in its root nodules, the pea is able to utilize nitrogen compounds which have been formed by using the free nitrogen of the soil air

Garden peas of a late or main-crop variety, known as Telephone, were planted Apr 10 They were sown in rows 30 inches distant and the plants were later thinned to 8 inches apart in the row

Early Development—The plants were excavated for the first time on May 23 They were 11 inches high and the stems 5 millimeters thick Each plant had two or three branches and about a dozen large compound leaves some of which were not fully developed The total leaf surface was 1 5 square feet

The plants had strong taproots about 4 millimeters in diameter at their origin These tapered to 1 millimeter in thickness below the 9-inch level Depths of penetration of 20 to 26 inches were found The course of the roots was often somewhat tortuous An examination of Fig 51 shows that the bulk of the absorbing area was furnished by the numerous, strong, lateral branches nearly all of which arose from the taproot in the surface soil Just below the seed, which was 1 inch deep, these occurred in great abundance. One rather large plant gave rise to 21 branches about 1 millimeter in diameter from the first inch, 14 nearly 1 millimeter thick from the second inch, 11 averaging ½ millimeter in diameter from the third inch, and 16 more, about ⅓

millimeter thick, in the next 6 inches The specimen drawn had only about two-thirds as many roots

The general course of these roots was outward and only slightly downward Thus nearly all ended in the first 6 to 9 inches of soil A few of the longest extended laterally 15 to 18 inches and then turned downward Depth of penetration, however, was not marked and only a few reached the 12- to 18-inch soil level Hence, the plant had a rather superficial root system at this stage

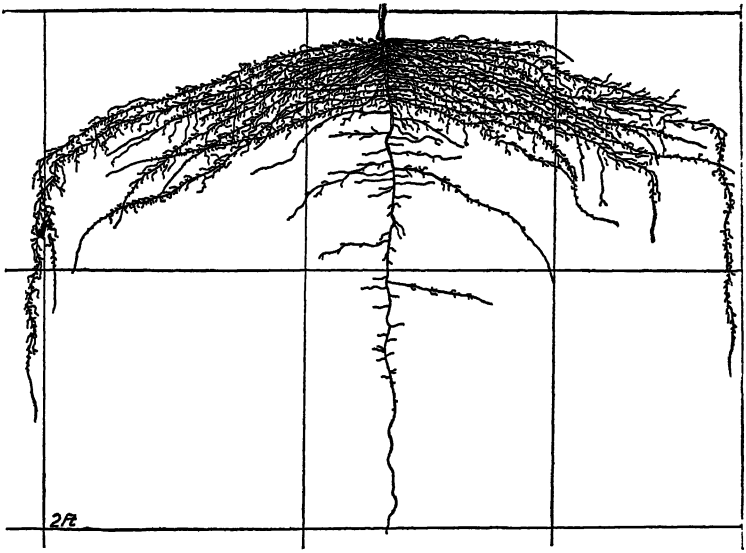


FIG 51 —Root system of the Telephone garden pea 6 weeks old

of growth The absence of roots in the surface 1 to 2 inches of soil is of interest since it bears a direct relation to root injury by cultivation

As regards branching of the taproot, it may be noted that some of the laterals, even in the surface 6 inches, were only 3 to 9 inches long Below this depth branching was much poorer as is clearly illustrated in the drawing The length of the laterals decreased with depth of origin and the last 4 to 6 inches of the taproot were unbranched This, of course, was also true of the major laterals These were furnished with rootlets at the rate of two to eight per inch, distribution being somewhat variable These sublaterals usually varied from 0 2 to 1 inch in length, although they were occasionally longer. They were rarely branched

Later Development.—A second examination was made June 17 when the peas were blossoming. There were about four branches per plant and these varied from 1 to 2.5 feet in length with an average length of 18 inches. Plants of average size possessed 45 leaves and a total leaf surface of slightly more than 5 square feet.

The pronounced taproots had increased to 7 millimeters in diameter near the soil surface. They tapered to 1.5 millimeters at a depth of 1 foot but were nearly 1 millimeter thick throughout their sinuous course. Maximum depths of 36 to 38 inches were ascertained. Branching had increased to a marked degree, a few roots 0.5 to 1 inch long now occurred in the first inch of soil. Frequently as many as 100 laterals were found to originate from a taproot in the first 12 inches of soil. A maximum of 18 per inch was determined. These were 0.5 to 2.5 millimeters in diameter. In the second and third foot—portions of the taproot which were poorly branched at the previous examination—a total of 110 to 130 rather uniformly distributed laterals frequently arose. The branches become longer, in general, on the older portions of the taproots. Near the root ends no branching occurred.

The lateral spread had increased only a few inches beyond that of the previous examination (now about 22 inches) but many of the widely spreading roots had turned downward and extended well into the second foot of soil. Moreover, the branching had progressed with the growth of the main laterals. Branches occurred at a somewhat variable rate, about seven per inch of lateral. This was also the usual rate of branching for the main laterals. Usually the branches were only 0.2 to 0.5 inch long although a few of them attained a length of 2 inches. Thus new soil areas were ramified for water and nutrients.

A pronounced feature was the greater number of branches on the portions of the laterals at some distance from their origin. In fact the first few inches were often poorly branched. Branchlets of the third order were more pronounced than at the previous examination although on the newer growth only the longest secondary laterals were rebranched. No long laterals arose below the first foot of soil but the very abundant short ones (1 to 3 inches) added considerably to the absorbing area.

In summarizing, four differences were apparent from the previous root development: The taproots had increased in depth from about 2 to 3 feet and the part below 10 inches had become clothed with a large number of short branches. The number of

lateral roots in the surface 12 inches of soil had greatly increased, especially on the second 6 inches of the taproot The widely spreading and some of the obliquely penetrating laterals had turned downward and extended well into the second foot of soil Finally, branching had greatly increased, older branches were somewhat longer and better rebranched and abundant new ones had arisen on the elongating roots Thus the second and third 6-inch soil levels were rather thoroughly ramified

Mature Plants —A final study was made July 11 The well-branched vines, which were 40 inches tall, were beginning to

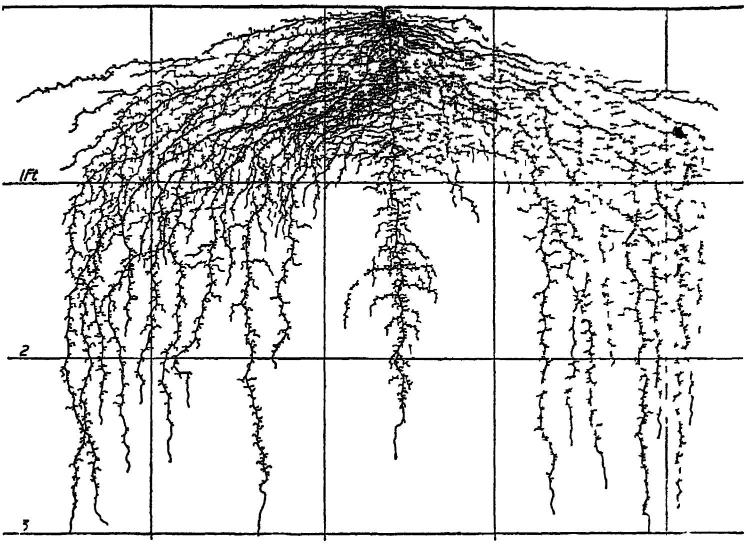


FIG 52 —Mature root system of the pea Note the large soil volume occupied and the greater degree of branching than at the earlier examination (Fig 51)

dry at the base The abundant pods bore peas which were half dry and too mature for use as green peas

The pronounced taproots were traced throughout their devious course which was usually characterized by gentle curves but often by abrupt, almost right-angled turns Depths of 3 to 3 2 feet were found This, however, was no greater than on June 17 The number of laterals, moreover, had not increased in the surface foot of soil The lateral spread was a little greater (maximum, 2 feet), more long secondary laterals occurred, and branches of the third order were much more frequent In addition to the more thorough ramification of the soil already

occupied, an extensive new volume of soil had been occupied by the downwardly penetrating main lateral roots At the June examination the longest of these did not extend beyond the second foot At this time the entire second foot was thoroughly ramified and much of the third foot was also occupied (Fig 52) This added greatly to the absorbing area

It is of interest to note that some of these roots extended to greater depths (maximum, 36 inches) than the taproot Also, their distribution was such that the soil volume below a depth of 1 foot and to 6 inches on all sides of the taproot was almost unoccupied Whether or not this was ramified later by an elongation of the branches of the taproot was not ascertained At this time the taproot below the first foot was furnished with relatively short branches Only rarely did they exceed 4 inches in length and they were frequently 0 5 to 2 inches long The number was, as before, about five per inch but they had not only grown in length but were also much more profusely rebranched Branches of the third order occurred on some of the older and longer laterals

This increase in length of branchlets also characterized the larger main branches Most of the branches of the second order ranged between 0 2 and 3 inches but not infrequently sublaterals 5 to 10 or more inches long occurred Branchlets of the third order seldom exceeded four per inch in number and ranged from 1 millimeter to 1 inch in length In the deeper soil, especially, secondary branches often took a horizontal course The roots were rather tough, of a tan color, and in many cases the root ends had dried

Summary—The garden pea is characterized by a strong taproot which in its early development is profusely branched only in the first 6 inches of soil Plants about 1 5 months old have a root depth of 2 feet The surface soil at a depth of 2 to 8 inches is well filled with a network of nearly horizontal roots and their laterals to a distance of 18 inches on all sides of the plant But in the deeper soil little absorbing area occurs About a month later, when the plants are blossoming, the root system is much more extensive and efficient The taproot is 3 feet long and much better branched throughout its entire course, secondary branches are longer and much more numerous, and branches of the third order abundant except on the youngest parts Lateral spread has been increased to 22 inches Many of the formerly

horizontal roots have turned downward and, with those penetrating more obliquely, fairly well occupied the second foot of soil

Nearly a month later, when the seeds are drying, the taproots have not increased in depth, nor has the number of main laterals increased in the surface soil But the soil volume earlier delimited is much more thoroughly occupied as a result of an elongation and more profuse branching of the finer laterals By a downward extension of the main laterals, moreover, the second foot of soil is well filled and the third foot fairly well ramified Branches from the taproot are profuse but rather short so that some of the deeper soil area directly beneath the plant is not fully occupied Thus the pea completes the development of an extensive absorbing system after the beginning of blossoming

Other Investigations on Peas—The British Queen pea was examined at Geneva, N Y, when the plants were 4 5 feet tall and the pods just past the marketable stage

> The taproot extended nearly perpendicularly downward to the depth of 39 inches Below this it was too delicate to trace Branches separated from the taproot throughout its length These were most numerous between 4 and 8 inches in depth, where they seemed nearly to fill the soil for a distance of about 8 inches on either side We traced a single branch root a distance of 18 inches from the taproot The majority of the branches appeared to extend little farther than 1 foot They gradually became shorter as the depth increased, but were 4 to 6 inches long at a depth of 30 inches Sometimes the branches curved upward after leaving the taproot [43]

The American Wonder pea was also examined at the same stage of development but the plant was only 6 inches tall The roots extended almost exclusively downward, the taproot reaching a depth of 30 inches No branches extended a distance greater than 4 inches from it [43]

Investigations in Russia indicate that although during germination and sprouting the vertical roots are rather short, later they make a uniform and rapid growth Plants only in the second-leaf stage had a root depth of 13 inches This was the only one of a number of vegetable crops studied that did not extend its vertical roots deeper after the inception of the flowering period The development of the horizontal roots at the beginning was very much less than that of the vertical ones But during the period of flowering these continued growth rapidly (after growth

of the vertical roots had ceased) increasing in length from 12 to 20.5 inches. A maximum root depth of 3 feet was attained.[123]

Numerous investigations on the pea have been made in Germany. In one it was found that it had a strong taproot that deeply penetrated with a marked early development of laterals which were especially abundant on the upper portion of the root system. These were found to extend in an obliquely outward and then downward course, many of them being nearly as long as the main root. Branching was profuse. In a good loam soil the Victoria pea was found to reach a depth of 18 inches and a spread of 12 inches when only 36 days old.[34]

Other investigations reveal a similar root habit, plants 1 foot tall having taproots 28 inches deep. The laterals attained a length of 10 inches. The upper laterals and their branches were usually much better developed than the lower ones. Occasionally, however, single branches arising deeply from the taproot made a good growth. Upon the loss of its tip, the taproot became covered with very numerous, long, much-branched laterals. These were augmented by a good adventitious root formation. Upon injury to the end of the taproot the laterals extended deeper than usual, those arising from near the injured end of the taproot growing more obliquely downward. Sometimes a single strong lateral turned vertically downward and, deeply penetrating, took the place of the taproot.[86]

In another experiment peas of the Victoria variety were grown in filled pits in a field of well-compacted loam. The soil was washed from the roots at various stages of their development. At the age of 32 days the roots of the seedling plants were more than 10 inches deep, 56 inches at the beginning of blossoming, 69 inches at the beginning of fruiting, and about 7 feet deep when the fruits were ripe. Thus the growth in depth increased rapidly at about blossoming time and continued until maturity of the fruit. Moreover, the later root development consisted largely in an increase in root depth and not in lateral spread. Nodules occurred to a depth of 67 inches but the bulk were in the upper 6.5-inch layer of soil. Later studies confirmed the deeply rooting habit.[133,134]

Another German investigator found that the pea was very similar to the common bean in its root habit. Like the bean, it formed a clearly defined taproot and then a row of adventitious roots which arose at first from the base of the hypocotyl but

later, in considerable numbers, from higher parts of the base of the stem These roots spread widely Depths of 28 to over 31 inches were attained [89] In another study it was found that the pea was most profusely branched to a depth of 4 inches and that the largest laterals had a length of 12 inches The number of laterals of the first order was about six per centimeter of taproot in the upper portion of the root system but only three on the deeper part Laterals of the second order varied from two to three per centimeter The deeper portion of the root system was only 52 per cent as well branched as the shallower part [35] Other European investigators have obtained similar results

Field peas, of the variety *arvense*, were examined at Fargo, N D , 86 days after planting and when the seed was ripe They showed a sparse growth of roots in comparison to top development The vines were 5 5 feet long but the roots reached a depth of only 3 feet and had rather a scanty supply of branches The bulk of the roots was found within 8 to 10 inches of the surface [149]

Recent experiments with peas at Greeley, Colo , where a dwarf variety (Nott's Excelsior) with a short root system was crossed with a tall variety (Telephone) with a deep root system, indicate that root characters are hereditary and segregate out in the F_2 generation according to the Mendelian ratios A repetition of the experiment under somewhat different conditions of growth confirmed the results, but it was also found that the dwarf variety had almost as long a root system as the taller one [67] This illustrates the fallacy of judging root extent by top growth After years of study of scores of native and cultivated plants, it has been fully demonstrated that such a criterion is entirely untrustworthy

A study of these investigations on different varieties of peas supports the conclusion that this species has a somewhat deeply rooting habit of growth The lateral spread is also similar to that already illustrated (Fig 52) and branching is quite profuse throughout Considerable root growth after the time of blossoming was found by most investigators, in some varieties this growth seemed to be chiefly that of the branches, in others an extension of the taproot Further studies, including adaptation of root system to different kinds of soil, are needed

The Development and Role of Root Tubercles.—Peas and other members of the family of legumes are the most important

plants, although not the only ones, that develop nodules or root tubercles Various strains[96] of a certain motile bacterium (*Pseudomonas radicicola*) live in the soil They gain entrance to the root system through the root hairs and push their way back into the cortical tissue of the root where they increase rapidly and occur in great numbers As a result of their activities, the cells of the cortex of the host make an abnormal growth which results in the well-known enlargements called *tubercles* These frequently occur at great depths On native legumes they have been repeatedly observed at depths of 10 to 13 feet Although usually most abundant on roots of garden crops in the surface 8 to 16 inches of soil, they are frequently found irregularly distributed over the root system at depths of several feet

The bacteria secure their supplies of water, carbohydrates, etc from the host plants but build up nitrogen compounds for which the source of nitrogen is the soil air From these compounds the legume secures large amounts of valuable nitrogenous material When the nodules decay, due to the activities of several other kinds of bacteria, the protein contents undergo various chemical changes and are finally left in the soil as nitrates, a most favorable source of nitrogen for green plants From 40 to over 250 pounds of nitrogen per acre may thus be added to the soil in a single season through the activities of tubercle-forming bacteria [18]

All parts of legumes are comparatively rich in proteins and are very valuable as fertilizers This explains why the practice of growing leguminous crops and plowing them under has such a stimulating effect upon the growth of succeeding crops On raw soils low in nitrates, such as railway cuts and embankments, where other plants can scarcely grow, certain leguminous plants, such as sweet clover, often thrive On the other hand, in a soil that is too rich nodule formation is not promoted

Experiments with the development of nodules on field peas and other legumes have shown that they become much larger when soil temperatures are most favorable A consistent increase in dry weight of nodules occurred as the soil temperature increased from 12 to about 24°C At higher temperatures (about 27 to 30°C for peas) a progressive decrease occurred [75] Likewise nodule production decreases as soil moisture diminishes below an optimum, or may entirely cease in soils that are very dry [35,180,68] A soil environment favorable to the growth of roots is also favorable to the growth of nodule-forming and many other species of

bacteria which promote crop growth Thus the promotion of proper soil aeration, water content, fertility, and temperature, so far as this is possible, affects plant growth not only directly by promoting root development and activities but also indirectly through its influence upon the activities of bacteria

Root Development in Relation to Cultural Practice—It would seem that plants with vigorously developed and quite extensive root systems like those of the pea would thrive on many kinds of soil In fact this has been ascertained to be true Undoubtedly the superficial and deeper portions are modified, respectively, so as best to adapt the plant to a particular environment Such modifications have been found for beans, the plants of which are closely related and of similar general root habit For early crops sandy loams are preferred because they are easily warmed But they do not retain the moisture and are often less fertile than heavier-soil types such as clay and silt loam The roots need good aeration and the soils must be well drained If the soil is too rich, the plants will develop large vines and ripening will be delayed

Thorough soil preparation is especially important where the crop is sown so thickly that cultivation is not possible This is true for a part of the market crops and the canning crop which is sown broadcast or in close drills Poor seed-bed preparation may result in markedly decreased yields[64] Otherwise the root habit would indicate that beneficial results will be obtained by frequent but shallow cultivation until the roots thoroughly ramify the soil and the vines cover the ground

The practice of deep planting permits the roots to start in moist, cool soil But it may increase the prevalence of root rot, a disease caused by a soil-borne fungus (*Thielavia basicola*), which grows best and does greater harm when more of the stem occurs below the soil[106] Because of the activities within the root tubercles, peas do not require such fertile soils or as heavy applications of manure as many other crops In fact large applications of manure do not increase the yields at the same rate as smaller ones[106]

Ordinarily peas are spaced so closely that when the plants are only partially developed, the roots thoroughly occupy all of the soil

CHAPTER XX

BEANS

Beans belong to a family of plants (the *Leguminosae*) which, with the possible exception of the grasses, ranks first in agricultural importance. There are many genera, species, and varieties of beans. The most important beans grown in the United States are the kidney bean (*Phaseolus vulgaris*) and lima beans (*Phaseolus limensis* and *P. lunatus*). Unlike the pea, which is a hardy cool-season crop, beans are sensitive to frost and require a warm soil and a warm season for their growth.

COMMON OR KIDNEY BEAN

The kidney bean is an annual, tall-twining plant. Dwarf varieties or bush beans (*P. vulgaris humilis*) are of low stature and of non-climbing habit. It is by far the most important species of bean grown in the United States. It is found in nearly every vegetable garden and is grown extensively on a commercial basis. There are 150 varieties of kidney beans in America.[66]

The Wardwell's Kidney Wax variety was used for root investigations. This is a wax-podded variety of bush bean. The crop was planted May 18, an earlier planting having frozen. The plants were spaced 6 inches apart in rows 2.5 feet distant.

Early Development.—The bean seedling is characterized by a very vigorous development of the taproot. Plants only in the cotyledon stage, but grown in warm, mellow soil, often have well-branched taproots 12 inches long.

Root development in the field was first examined June 18. The plants were already 5 to 6 inches tall and had a spread of 10 inches. Each had about 10 leaves, the leaflets being 3 to 4 inches long and 2 to nearly 3 inches broad. The total leaf surface averaged 1.4 square feet.

The root system was characterized by a strong, nearly vertically descending taproot and multitudes of long, horizontal branches arising mostly in the 2- to 6-inch soil level (Fig. 53).

Some of these large branches, as in the lima bean, were adventitious, arising from the base of the stem. Although a few of the horizontal roots were over 2 feet long, their course was so devious that the maximum lateral spread was slightly less than 2 feet. Usually only about 25 roots per plant exceeded a length of 6 inches. Shorter ones were very numerous. For example, between depths of 3 and 8 inches there was usually found a total of 21 roots per inch, although at greater depths they were less numerous (*e.g.*, 7 per inch between 9 and 14 inches, inclusive).

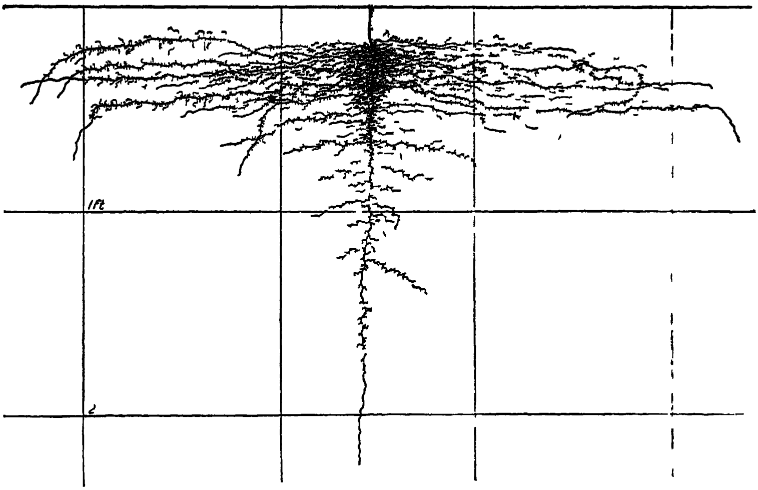


FIG. 53.—A month-old root system of Wardwell's Kidney Wax bean.

As a rule many of the shorter, horizontal roots, only 2 to 4 inches long, were unbranched or only poorly furnished with laterals. On the longer ones branching occurred at the average rate of 10 branchlets per inch. These varied from 0.2 to 2 inches in length. A very few were 4 to 8 inches long and possessed branches of the third order. Thus the soil to a depth of 8 inches was quite well occupied by a network of rootlets. These are shown in Fig. 54 which is a surface view of the roots in the first 6 inches of soil.

A comparison of the horizontal view with the vertical one gives an adequate picture of the root extent and position. That the roots were elongating rapidly was shown by the 3 or more inches of unbranched root ends. Also the future, obliquely downward

course could already be predicted by the position of the root termini

The taproot, below the 8-inch level, was well clothed with rootlets (Fig 53) Only those exceeding 3 to 6 inches in length were rebranched The last 5 inches of the turgid, thick, white taproots were quite smooth, although considerably kinked and

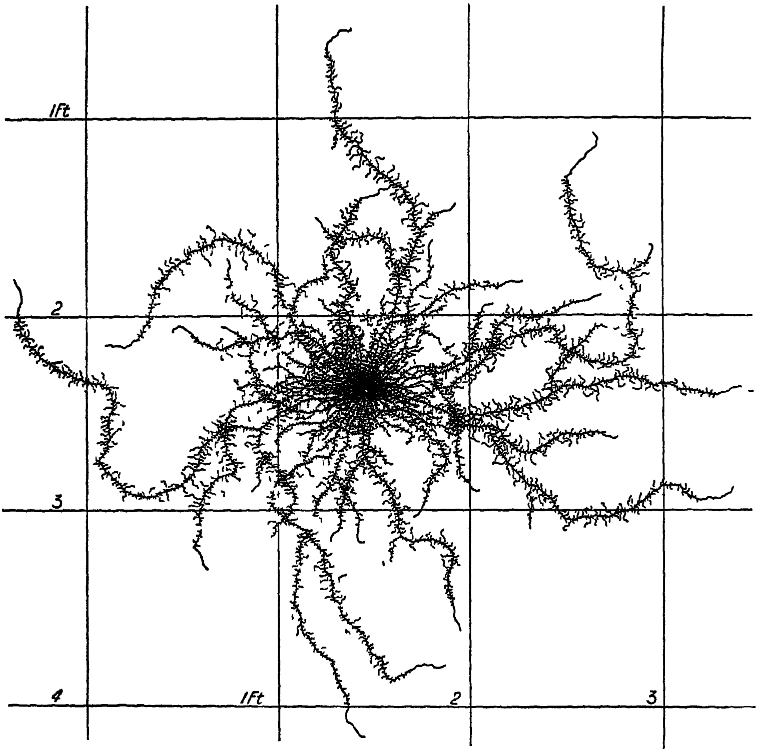


FIG 54—Surface view of the roots of the bean in the first 6 inches of soil Compare with Fig 53

curved from penetrating the compact soil A maximum depth of 27 inches was ascertained

Midsummer Growth.—A second examination was made about a month later, on July 14 The plants were now nearly 1 foot high and had a spread of approximately 1 foot Those of average size possessed about 18 large leaves, the largest of which were over 1 foot in width The largest leaflets had a length and diameter of 6 and 5 inches, respectively The transpiring surface

had increased to 5.5 square feet. The plants were blooming profusely and numerous young fruits were growing vigorously.

The roots too had made considerable growth, although this was not so marked as in many other vegetable crops. The lateral spread reached a maximum of 30 inches, the most widely spreading roots sometimes ending in the surface foot of soil.

Where the tips of the roots had been injured or destroyed, numerous laterals arose from the root ends and some of them

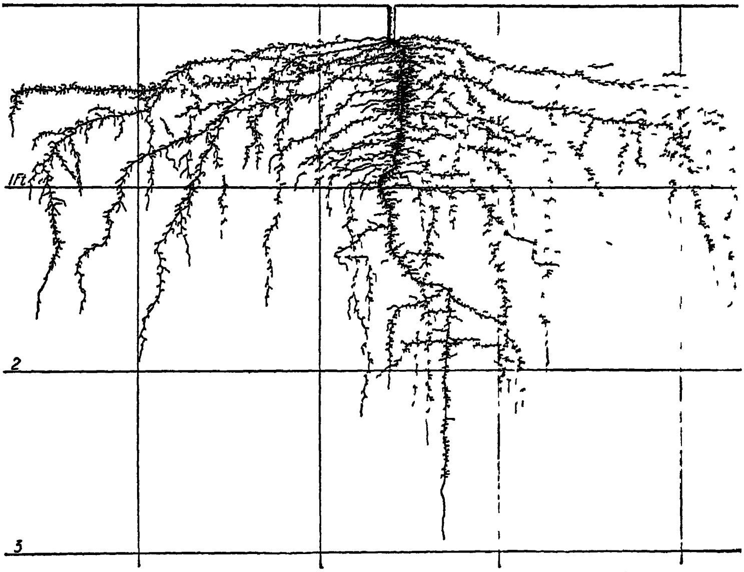


Fig. 55.—Root system of kidney bean about 2 months old.

pursued the course which would have been taken by the main root. This phenomenon of the growth of laterals being promoted by injury to the main branch has been repeatedly observed among many vegetable and field crops.

The taproots had also increased their depth from about 27 inches at the June examination to 3 feet. Likewise the working level (exclusive of taproot) which scarcely exceeded 12 inches, had now been extended to an approximate depth of 20 inches.

As before, considerable variation was found in the total number of large main roots. On the plant selected for drawing, most of these, as in the lima bean, arose from the base of the enlarged stem. Sometimes the taproot furnished more of them. A comparison of Figs. 53 and 55 shows that the roots on the plant

selected to represent the later stage are scarcely as horizontal as those in the earlier drawing This is largely due to variations in the individuals The downward growth of these widely spreading, as well as the more obliquely growing, roots is here well under way

These strong main or lateral roots had diameters of 2 to 3 millimeters and were at least 1 millimeter thick throughout their course The rate of branching was, as before, about 10 laterals per inch of root They varied from 3 to 15 but usually approached the higher number Many of them were only 0 2 to 1 inch in length, especially on the younger portions of the older roots and on the longer branches of the old ones The latter were now abundant and ranged from over 1 inch to 6 inches in length They were usually profusely rebranched, roots of the fourth order being not uncommon Frequently, the branches occurred in clusters of threes on opposite sides of the roots The general direction of these large branches, their lax and often sinuous course, and the degree of branching may best be visualized by a study of the drawing

As regards the taproot, it plays an important rôle Filling the soil with its numerous branches just below the plant and extending considerably beyond the working level of the other roots, it continually drew upon new sources of supplies Although some taproots were quite vertical in direction of growth, others pursued a very devious route as is shown in the drawing As before, many short branches came from the older, shallower portion These were better rebranched than at the earlier examination Moreover, numerous, long, well-branched laterals, running in various directions, had developed and added greatly to the absorbing area As on all the major roots, and indeed many of the smaller ones, the 3 or more inches of unbranched, glistening white tips showed that the plants were still growing rapidly

Mature Plants —A final study of the kidney bean was made Aug 5 The very leafy plants were about 13 inches tall and had a total spread of 15 inches Although some were still blossoming, most of them had an abundance of mature pods That they were fully grown was shown by the drying of some of the leaves

The roots had not increased in lateral spread but the taproots and some of the longest main laterals (including those arising adventitiously from the stem) had extended to depths of 40 to 46 inches. The working level had also been greatly increased, *i e*,

from 20 to 36 inches Root branching was very well developed to the 3-foot level and to a distance of 2 feet on all sides of the plant Many roots extended deeper A few, especially the deeper portion of the taproots, showed signs of decay

Summary —The kidney bean rapidly develops a deeply penetrating taproot On plants 31 days old and 6 inches tall this reaches a length of over 2 feet Branching is profuse throughout but especially in the 10 inches next to the surface Roots from the base of the stem and from the taproot extend horizontally but deviously in the second to the eighth inch of soil to distances of 12 to 24 inches With the numerous branches they constitute the bulk of the absorbing system which is distinctly superficial A month later, when blossoming is profuse and fruits beginning to form, the roots are more extensive The taproot has increased its depth to 3 feet and the working level to 20 inches It is widely branched even in the second foot of soil The main horizontal branches have extended the lateral spread to 30 inches and have branches which penetrate far into the second foot of soil When the plants are nearly mature, the soil to 2 feet on all sides is well ramified to a working level of 3 feet and numerous roots extend 1 foot deeper

Thus the general root habit of the kidney bean is not greatly unlike that of the pea although the lateral spread and depth of penetration are somewhat greater and the deeper soil, just beneath the plant, somewhat more thoroughly occupied

LIMA BEAN

The large lima bean (*Phaseolus limensis*), although a perennial in the South where it is of considerable commercial importance is grown as an annual in northern United States It is a vigorous grower but requires higher temperatures and a longer growing season than the common garden beans It is a stout, high-climbing plant although bush or dwarf forms do not climb

Burpee's Bush Lima bean (variety *limenanus*) of the large-seeded, flat type was planted June 2 in rows 30 inches distant The seeds were placed 6 to 12 inches apart in the row

Early Growth —The root system was first examined 2 weeks later on June 18 The cotyledons were yellowing and nearly every plant was furnished with two leaves each about 4 inches long and one-half as wide The total leaf surface was 24 square inches The plants averaged 5 inches tall

A strong taproot extended from the base of the stem and reached a depth of 13 inches The very numerous, mostly horizontal branches were longest above (maximum, 9 inches) and gradually became shorter at greater depths, thus giving a conical shape to the root system as a whole (Fig 56) No roots were found in the surface 2 inches of soil but numerous, large, adventitious roots arose from the base of the stem and spread widely just below this soil level They were growing rapidly and the last

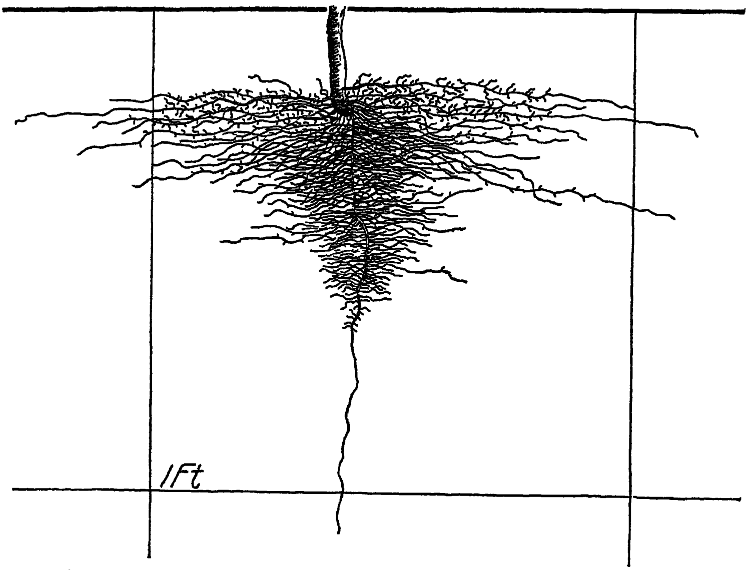


FIG 56 —A 16-day-old root system of Burpee's Bush Lima bean

3 inches were quite unbranched Otherwise branches of the first order only 0 3 to 2 inches long (but mostly short) occurred at the rate of about 8 per inch From the older portion of the taproot, *i e*, the first 5 inches, laterals arose in great numbers, often as many as 30 per inch These varied in length from about 4 inches on the older part of the taproot to 1 millimeter on the younger portion The last 4 inches of the taproot were unbranched

Midsummer Growth —About 5 weeks later, on July 24, a second examination was made The plants were 10 inches high and in bloom The stout stems bore approximately 33 leaves each The largest leaflets were 3 5 by 2 inches in length and breadth, respectively, and the total transpiring surface was 4 3 square feet

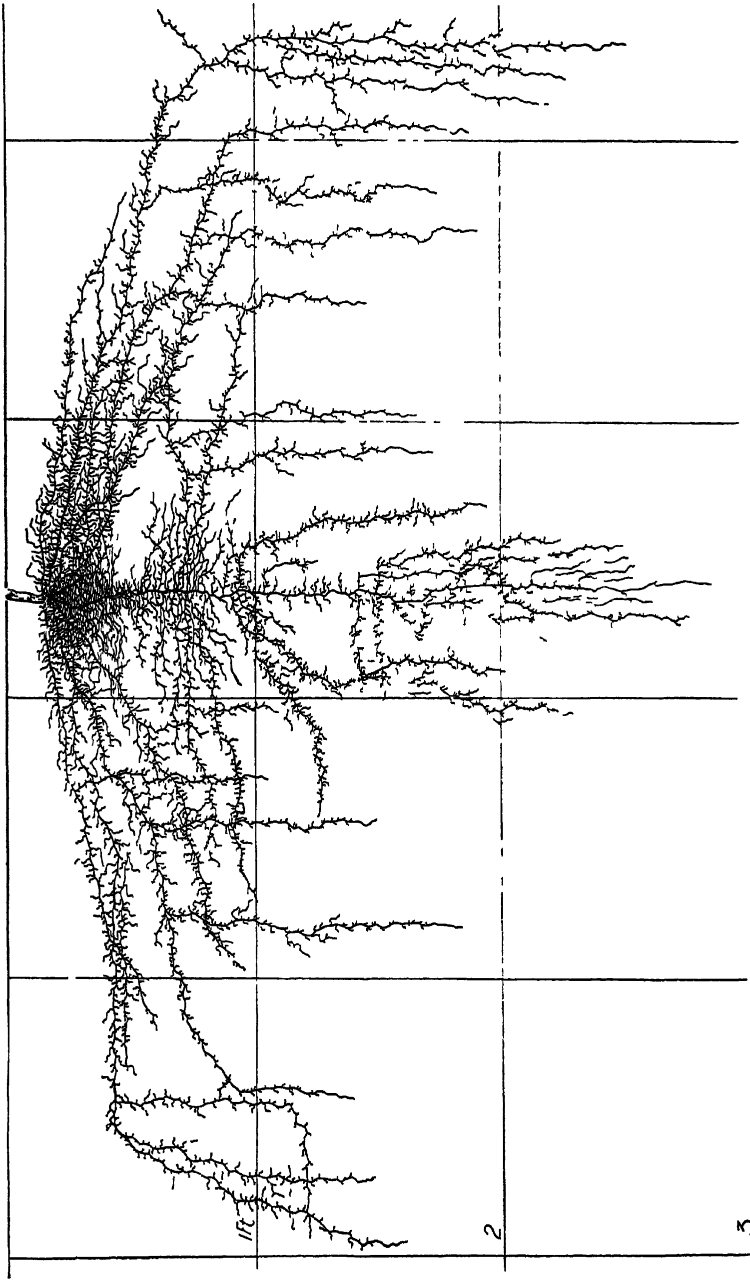


FIG. 57.—Root system of lima bean at the time of blossoming (July 21)

The root system also had made a good growth The lateral spread had increased to over 2 feet and a depth of nearly 3 feet had been attained A root system was usually composed of a taproot and 6 to 8 large laterals arising from the base of the enlarged stem, although there always were numerous, smaller rootlets The taproot pursued a somewhat devious downward course, often kinking and turning either in long, graceful curves or abruptly and penetrated deepest, 33 to 35 inches The more superficial large roots spread laterally, often 1 to 2 feet in the surface 8 inches of soil, and then turning more obliquely or even vertically downward reached depths of 20 to 30 inches Still other main roots, running more obliquely downward, filled in the soil volume between the widely spreading laterals and the area occupied by the taproot and its branches (Fig 57) These large roots were 1 to 2 millimeters in diameter and maintained this thickness throughout their course

Branching on the laterals was somewhat variable but, in general, it was profuse The shorter branches were simple, mostly only 0 3 to 2 inches long, and occurred usually at the rate of 4 to 12 per inch The longer branches, *i e*, those exceeding 2 to 3 inches in length were practically all furnished with laterals and at a rate similar to that of the main branch Frequently, they were 9 to 15 inches in length

On the taproot branching was very profuse, 25 to 28 laterals 0 2 to 4 inches long occurred on each inch through the first few inches of its course Branching was especially pronounced in the furrow slice (first 8 to 9 inches, Fig 57), some of the horizontal branches spreading rather widely and sometimes giving rise to long, vertically penetrating rootlets At greater depths they showed a distinct tendency to spread a few inches and then turn downward, often paralleling the course of the taproot for 1 foot or more The longest branches were already furnished with tertiary roots Thus the plants had a very efficient absorbing system

Maturing Plants.—The final examination was made Aug 25 The plants were well developed and in fruit They were 19 inches high, had a total spread of tops of 30 inches, and had not yet begun to dry About 25 branches were found on plants of average development These were covered with an abundance of large, green leaves Many large pods, nearly 5 inches long and over 1 inch wide, as well as numerous smaller ones, were

found on normally developed plants Blossoming had just ceased

The underground parts had made a striking development The lateral spread had doubled, now extending to a maximum of 4 feet, the depth of penetration had been increased from 3 to 5 5 feet, and the working level to 45 inches Usually the stem extended 2 to 2 5 inches into the soil and gave rise to a deep taproot on its terminal portion and almost equally large laterals from near its base The latter were usually 7 or 8 in number (sometimes there were as many as 11) and in length and degree of branching they were often quite as important as the taproot In cases where these lateral roots were fewer (sometimes only 4 in number) the taproot gave rise to many strong, well-developed laterals The taproot and the large adventitious roots from the stem varied from 1 5 to 3 millimeters in thickness, usually the taproot having the larger size Nearly all maintained this diameter for the first 12 to 18 inches of their course and some maintained it through a distance of 5 feet or more to their ends Occasionally, a root would taper to 1 millimeter in thickness and then again enlarge

The taproot alone pursued a generally vertically downward although somewhat meandering, course and extended more deeply Most of the other main roots ran 1 to 3 or more feet in the surface 6 to 12 inches before turning downward They sometimes forked, however, and gave rise to groups of three to five branches which ran more or less vertically downward into the third or fourth foot of soil Moreover, nearly all of these roots gave rise in their horizontal course to vertically descending, major branches Some of these grew only 6 inches from the taproot, others grew over 3 feet from it These roots, with their branches very completely occupied the soil to the working level at 45 inches (Fig 58)

The rate of branching was somewhat variable, both as to number and length of laterals, but it was always profuse A rate of 6 to 12 per inch was common, and 13 to 16 per inch not unusual The smaller branches ranged from 0 1 to 5 inches in length Most of these, especially the longer ones above the 2 5-foot level, were supplied with laterals of the second order at a similar rate Rootlets of the third order were not uncommon Longer laterals, many of which have already been mentioned as descending vertically, were rebranched like the main roots Although

the first few inches on the main lateral roots were not so well furnished with branches, this area was extremely well occupied by short laterals (0.5 to 2 inches long) arising from the taproot. For example, 72 of these were found between depths of 3 and 9 inches. These thread-like outgrowths were usually unbranched. Between the depths of 8 and 15 inches the roots were only about half as numerous, usually 1 to 4 inches long with 10 to 15 branches per inch. These were rebranched often

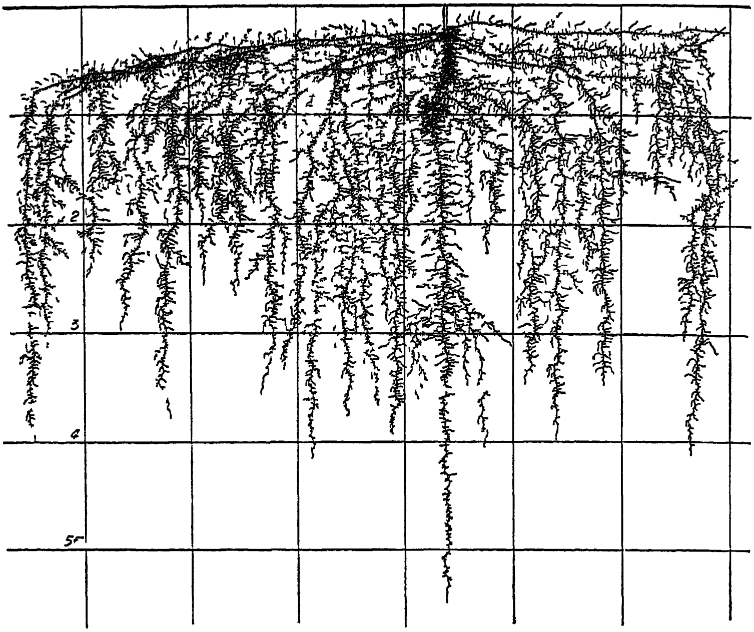


FIG. 58.—The great extent of a maturing lima bean plant is here shown. Two hundred cubic feet of soil were ramified by the roots of a single plant.

to the second order, thus forming an efficient root network surrounding the taproot. Below this to a depth of over 2 feet branching was again more abundant and the branches averaged much longer. They were very short and little absorption occurred below the 4-foot level.

Summary.—The root system of the lima bean is very similar to that of the kidney bean. In early growth it develops a taproot with very abundant horizontal lateral branches, others arise adventitiously from the base of the stem. The root

system is conical in shape, the base of the inverted cone beginning about 2 inches below the soil surface During the 5 weeks following, about eight strong lateral roots spread 2 feet or more in the surface foot of soil, branching profusely Turning downward they end in the second or third foot Large numbers of smaller laterals fill the soil near the taproot The taproot is also covered with long laterals almost to its end, approximately at the 3-foot level, which greatly increases its absorbing area

By the end of blossoming the root system has made further marked growth Widely spreading, nearly horizontal branches run outward 2 to 4 feet in the surface 12 inches Then they often turn downward and, like the long laterals arising in their horizontal course, penetrate deeply, frequently far into the fourth foot of soil More obliquely descending long roots and shorter branches arising from the taproot (which was 5 5 feet long) fill in the remaining soil volume just beneath the plant Often the major branches are as important as the taproot Where they are few, the deeper portions of the taproot are better branched An intricate network of small rootlets occurs throughout the 200 to 225 cubic feet of soil ramified by a single plant The lateral spread of roots is about 4 feet This is 1 5 feet greater than that of the kidney bean, and the working depth is about 9 inches deeper The larger root system of the lima bean correlates with the greater development of tops

Other Investigations on Beans—Many studies have been made upon the root habits of beans especially in Europe Certain German investigators have found that the bean (*Phaseolus vulgaris*) and the vetch or broad bean (*Vicia faba*) are very similar in their root habits Both of them form a clearly defined taproot and then rows of adventitious roots The latter arise at first from the base of the hypocotyl but later, with the increasing age of the plant, they arise in considerable numbers from higher parts of the stem base In the bean, these were found to be developed almost as strongly as the main root The stronger root branches of the first order, which occurred in great numbers, especially in the bean, penetrated to about the same depth as the main root The depth of penetration in the bean was 40 to 43 inches The lateral spread varied from 20 to 30 inches [89] Similar results in regard to depths of penetration have been found by other investigators [133]

Two varieties of *Phaseolus*, Pride of Lyon and Princess of Orleans, have been carefully studied in Russia The first had

the same depth of root penetration (25 inches) at the age of 45 days as did the latter when it was 10 days older At the beginning of the flowering period the relative depth and lateral spread for the two species were 26 and 10 inches for the former and 30 and 12 inches for the latter The fact that different varieties have a different root extent was clearly indicated Princess of Orleans had a weaker growth of roots which ceased development earlier than the more extensive root system of the Pride of Lyon The final root depths were about 34 and 38 inches and the lateral spread was 12 and 20 5 inches, respectively Beginning with the flowering period, the horizontal roots increased in length only slightly [123]

The Boston Dwarf Wax bean was grown at Geneva, N Y , and washed from the soil about the middle of August when the plant was approaching maturity The soil was a clay loam, 6 to 10 inches deep, underlaid by a tenacious gravelly clay subsoil The deeper roots were traced to a depth of 2 feet and the horizontal ones extended quite as far on either side of the plant The Scarlet Runner bean was also examined at the same time The stems were about 4 feet high and the plant was in full bloom The deeper roots extended to 2 5 feet and the longer horizontal ones at least a distance of 4 feet A few roots grew within 1 inch of the surface, but the great majority were between 2 and 8 inches in depth The root system was very similar to that of the wax bean but decidedly more extensive [44]

Other studies have shown that the kidney bean, the scarlet runner, and the lima bean are all characterized by a rather strong taproot When the taproot meets obstacles, it is easily turned aside from its course or may break up into many branches Laterals of the first order are very numerous, develop early, and are abundantly clothed with much-branched laterals of the second order The lateral spread was found to be greater than that of the pea Bean plants only 36 days old reached a depth of 12 inches and had a lateral spread of 20 inches [34]

It has been found that the root system of the kidney bean is capable of considerable modification In a loose, rich soil the roots are able to extend their depth of penetration by promoting the growth of the taproot and strong, basal, outwardly and downwardly penetrating roots This is accompanied by a decrease in branch production, somewhat directly proportional to depth But if the root tips are disturbed by cultivation, the

laterals arising from these roots, which are already long and thick, are much more limited in downward growth Thus the bean also has the ability to adapt itself to shallow soil Since the stronger roots are hindered from penetrating deeply, they produce more numerous and longer laterals and the basal roots arising later pursue a more horizontal course [36]

The broad bean (*Vicia faba*) has a root habit very much like that of the navy bean with strong, widely spreading laterals arising from the upper portion of the taproot and more obliquely penetrating branches from the deeper part It was experimentally determined, by growing beans in boxes 6 and 14 in in depth, respectively, and filled with the same volume of soil, that the taproots were much shorter in shallow than in deep soil, but that the number of secondary roots per unit length was greater in the shallow soil When the taproot was cut, no injury to the plant ensued provided the cutting was far enough below the surface so that sufficient taproot was left to produce an abundance of laterals Free development of the taproot to a considerable depth was found unnecessary to the best growth of the plants under the conditions of the experiment But where the deeper layers of the soil were to be utilized the taproot is needed to give rise to the deeper laterals That the plant adapts itself to shallow soil by modifying the usual root habit is a fact of great significance and of much importance to agriculture [34]

In another experiment broad beans were grown in a field of loam soil When the plants were 4 to 5 inches tall, the upper lateral roots were cut close to the plants to a depth of 6 inches This was done at midday early in June The weather was clear and hot, following ample rains The plants soon wilted and, in fact, wilting was noticeable for several days On some of the plants the lower leaves died The plants grew poorly and had increased very little in height by July 1 when a second, similar cutting was made They did not wilt following the second cutting, but even a month later they were much more poorly developed than uninjured plants On the other hand, cutting of the taproot of other plants below the main branches, *i e*, at a depth of 6 inches, did not result in wilting although at the time this was done the soil was quite dry It was demonstrated by other experiments that deep tillage gives greater returns where the plants are widely spaced than where they are grown closely together [85] The relation to root injury is apparent

Other investigations on the broad bean showed that it was most profusely branched to a depth of 4 inches and that the largest laterals had a length of 10.5 inches. The number of laterals of the first order was about seven per centimeter of taproot in the upper portion of the root system but on the lower part there were only about two per centimeter. The deeper portion of the root system was only 29 per cent as well branched as the shallower part. Thus, in comparison with the pea examined at the same time, the maximum length of branches was 1.1 inches less, but the number of primary laterals was somewhat greater in the surface soil. On the primary and the secondary laterals of the pea the branches were two to three times as numerous in the deeper soil and the total branching 23 per cent greater (relative to the shallower portion of the root system) than in the case of the bean.

The roots of the large, flat lima bean, grown in California, extend to depths of 3.5 to 6 feet. The taproot penetrates almost straight downward to this depth, giving rise to smaller and more fibrous rootlets at intervals. Where the water table is at such a level that the roots of the plants penetrate down to the moisture which arises from it by capillarity, the beans do exceedingly well and are not so badly affected by the hot, dry days. They will endure very dry soil on the surface after their roots become established below. In tropical climates the root is sometimes large and fleshy and the plant lives more than 1 year.[137]

A survey of these investigations on the rooting habits of beans points clearly to the fallacy of the current idea, commonly expressed in the literature on vegetable growing, that beans are a shallow-rooted crop. It is true that a portion of the root system lies just beneath the surface of the soil, but the roots also extend widely and penetrate deeply. Among the varieties studied considerable differences were found in the rooting habit and the ability of the root system to adjust itself to different soil environments has been shown. Further studies of these and others of the very numerous varieties will throw much light upon root behavior under various conditions of growth. How the roots respond in their distribution and activities under dry-land culture, irrigation, various methods of seed-bed preparation, depth and method of distributing manures and other fertilizers, depths of intertillage, etc. are problems awaiting further investigation.[85] More attention should be given to their activities in the subsoil. These

will be found not only of great scientific interest but may lead to modifications and improvements of current cultural practices.

Root Habit in Relation to Cultural Practice.—The widely spreading roots of beans, the fact that they are richly furnished with tubercles, and the plasticity of the root system in adapting itself to various environments, all lead to the conclusion that beans will grow well in various types of soil. The fact that they do quite well in practically all types from light sandy loams to heavy clays is well known by most gardeners. That the common beans will thrive on poor soils better than many other crops is expressed in the vernacular, "It is good enough for beans." In the North, however, clay soils may be too wet and warm too slowly, and sandy soils may be too droughty.

The plants respond in root development and yield when grown in moderately fertile, carefully prepared, well-drained but moist and properly cultivated, non-acid soil. The bean plant is especially sensitive to poor tilth and rough treatment at the time of cultivation. A good seed bed, well pulverized and firmly packed, permits the maximum utilization of the soil nutrients and moisture throughout the entire growing season. In a poorly prepared seed bed the fibrous roots may die and the plant be handicapped by the partial or complete loss of that portion of its root system occupying the richest part of the soil. On soils that are too rich there is a tendency toward too great a growth of vines and, undoubtedly, a compact root system.

Since both kidney and lima beans are epigeal in habit and the large cotyledons must be pulled out of the ground, thorough preparation and good tilth of a well-compacted seed bed are essential. A deep, mellow soil promotes deeper root development and at the same time a more thorough occupancy of the richest portion of the substratum, the surface soil layer. This is due in part to better aeration and partly to better water-holding capacity of the soil. In dry-land farming this early stirring of the soil forms a dry soil layer. If this is maintained, the plants will root only below this layer. Otherwise many surface roots would undoubtedly die as a result of later drought.

Under irrigation, where a furrow is to be made between the rows to permit watering while the crop is growing, it is the practice to cultivate deeply this part of the soil. This is a precaution to keep the soil dry and thus prevent the roots from extending into the area so that they will not be injured when the

furrow is opened [144] Hoeing the soil about the stems promotes the production of very many adventitious roots Subsoiling to a depth of 16 to 18 inches is advocated to increase moisture penetration in more arid districts [55] In certain sections where beans have been grown for many years, it is necessary to practice crop rotation as a preventive measure against dry root rot This disease is caused by a soil-borne fungus (*Fusarium martii phaseoli*) It appears as a reddish-brown dry rot at the base of the plant and often causes the loss of almost the entire portion of the finer roots as well as the shriveling of the end of the taproot

Early cultivation close to the plant is undoubtedly beneficial but the rate of lateral root growth should be carefully considered By adapting their roots to a shallow soil, beans are limited in their range for securing nutrients Their roots are thus unfavorably situated for enduring drought The plants quickly develop and soon completely cover the ground, preventing rapid evaporation of moisture from the soil should it escape absorption by the network of surface rootlets Early cultivation should be shallow to avoid root injury A late crop of beans showed very little advantage in cultivation over keeping the weeds down by scraping the surface [152]

Proper spacing of the plants is an important feature of vegetable production Crowding reduces the growth of tops and this in turn results in a poorly developed root system Larger varieties and plants grown on rich soil where there is little danger of drought or where irrigation is used are more widely spaced Where moisture is the limiting factor in growth, as in dry farming, wide spacing is imperative For example, in Colorado under irrigation the rows are spaced 28 inches distant, but on dry lands they are spaced 36 to 42 inches apart The plants are spaced 4 to 6 inches apart in the row under the first condition and 10 to 12 inches under the latter [77]

Drilling the seeds 4 to 6 inches apart gives a better distribution of the plants than placing five to eight seeds in a hill 2 5 to 3 feet distant This former method at least partially eliminates crowding Experiments have shown that where field beans were planted at the rate of five per hill, and the hills spaced 18 inches apart in rows 3 feet distant, the yield was hardly more than one-half of the yield where the beans were spaced 6 inches apart in the row [28] Garden beans are usually spaced too closely[38] as may be readily seen by an examination of the rooting habit

CHAPTER XXI

OKRA

Okra or gumbo (*Hibiscus esculentus*) is a stout, erect, branching plant, 1.5 to 6 feet tall. Like cotton, it belongs to the family of mallows. The plants are cultivated as annuals for their large, soft, immature pods. Although of no great importance in the United States, it is commonly found in home gardens in the South. It is a tender plant and thrives best in hot weather.

Seed of the Mammoth long-podded variety was planted at Norman, Okla., in rows 3.5 feet apart, Apr. 27. Several seeds were placed in a hill, but later the seedlings were thinned to single strong plants 3 feet apart.

Early Development.—About 3 weeks later (May 20) the plants were 5 inches tall and each possessed 4 leaves with blades 2 to 2.5

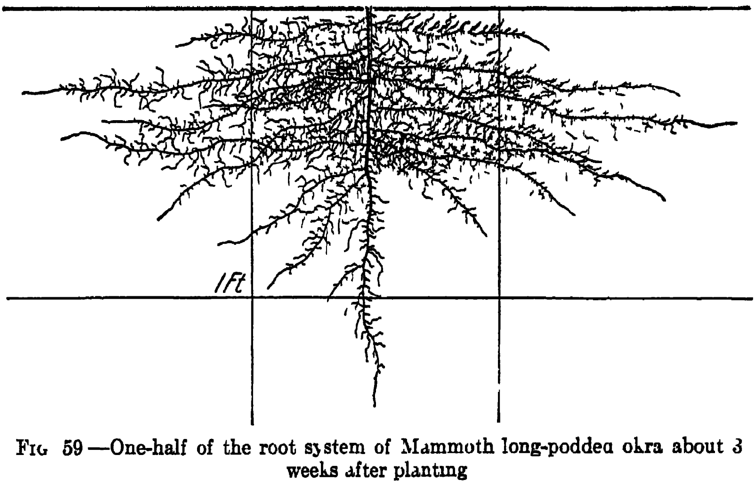


FIG. 59.—One-half of the root system of Mammoth long-podded okra about 3 weeks after planting.

inches in length. Okra has a strong taproot which penetrates almost vertically downward. The taproot was about 5 millimeters in diameter and reached a depth of 16 inches. A total of 24 to 35 laterals, the largest 1.5 millimeters thick, ran horizontally from just beneath the soil surface to a depth of 8 inches. The roots originated on four sides of the taproot. A maximum spread

of 18 inches was reached at the 5-inch level A few of the deeper laterals pursued an obliquely downward course All were furnished with a profuse growth of laterals 0 1 to 3 inches in length The rate of branching was about 8 laterals per inch (Fig 59) The roots were white and rather tender

Later Development—The branched stems had reached a height of 8 inches by June 12 They were ½ inch in diameter

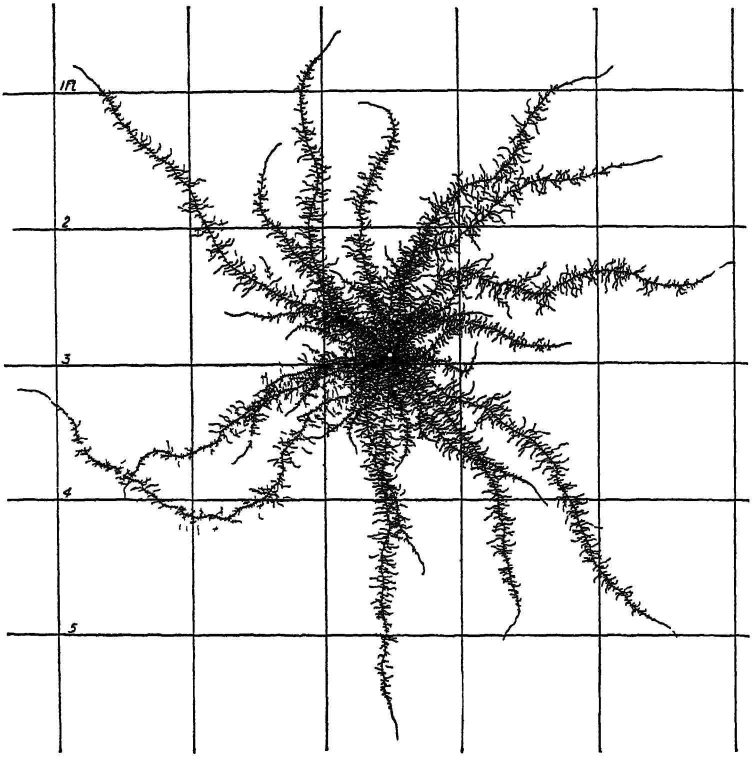


FIG 60—Surface view of the roots of okra occupying the first foot of soil The plant is 46 days old

and clothed with numerous leaves, the largest being 8 inches in width Flower buds were appearing The strong taproots tapered rapidly from 12 millimeters in diameter near the soil surface to 1 millimeter at a depth of 10 inches They pursued their rather vertically downward course to depths of 20 to 22 inches The strong laterals in the surface 8 inches of soil ran in a generally horizontal course to distances of 15 to 32 inches

from the base of the plant A total of 29 roots was found on a plant of average size on the first 8 inches of taproot These are shown in surface view in Fig 60 The widely divergent roots were branched at the rate of 4 to 6 laterals per inch, only the longest bore sublaterals Thus a rather large volume of the rich, moist, surface soil was quite well ramified Below 8 inches the branches were almost as numerous but decreased rapidly in length toward the growing tip from a maximum length of only 5 inches The white, slightly fleshy roots were rather tough

Maturing Plants —By July 22 the well-branched plants were 4 5 feet tall and had a stem diameter of 2 inches They had made such a vigorous growth that the soil between the 3 5-foot rows was quite concealed The plants had been fruiting for some time and the pods were exceptionally large Growth, however, was proceeding vigorously

The taproot, now nearly 2 inches thick near the soil surface gave rise to so many major branches that it tapered rapidly, and was only 3 millimeters in diameter at a depth of 1 foot It pursued a rather devious downward course to a depth of 4 5 feet The laterals of the surface 8 inches had increased enormously in size From 11 to 17 were found on various plants with diameters of 5 to 20 millimeters Even 2 feet from the base of the plant some of these strong roots were 3 millimeters thick

The maximum lateral spread had been increased from 32 inches (June 12) to 79 inches Many roots, of course, did not spread so widely But nearly all of those originating in the surface 8 inches ended near the soil surface or turned downward near their extremities for only a few inches The branches below the 8-inch level had also made a vigorous development Several laterals 1 to 2 millimeters thick originated from the taproot at depths of 10 to 20 inches These ran outward and downward or outward for only a few inches and then turned abruptly downward and paralleled the course of the taproot Frequently, they reached depths even greater than that of the taproot Aside from these larger roots numerous others occurred in the four rows on the sides of the taproot Usually about 8 to 12 roots arose from each inch of the taproot

Large branches, sometimes 3 to 4 feet long, now arose from the major branches In general, these pursued a horizontal direction Like the other roots they were clothed with a great network of rootlets at a rate varying from 4 to 12 per inch.

Summary—Young plants of okra have a strong taproot and many nearly equally long, mostly horizontal branches whose numerous laterals fill the surface 8 inches of soil When the flower buds appear, the 25 or more horizontally spreading roots extend from 0 5 to 2 5 feet from the base of the plant They are well furnished with absorbing rootlets The taproot attains approximately a depth of 2 feet, but below 8 inches the branches are short Mature plants have taproots 2 inches thick and 4 5 feet deep The surface laterals become much thickened and extend widely, some to 6 feet Some turn downward a few inches near their ends but none penetrate deeply Several branches originate below the 8-inch level, running obliquely outward and then far downward, they supplement the absorbing area of the well-branched taproot Thus the root system consists of two rather distinct parts a shallow, widely spreading portion thoroughly ramifying the surface 18 inches of soil to a distance of 6 feet on all sides of the plant, and a deeply penetrating, well-branched taproot which gains access to the water and nutrients in a soil column about 2 feet thick and which extends to a 4-foot level This latter portion of the root system develops rather late Thus the soil between the widely spaced plants is thoroughly occupied

Other Investigations on Okra—The roots of a plant of a dwarf variety of okra were washed from the soil at Geneva, N Y, in September

The longer roots extended several inches into the compact clay subsoil At a depth of 18 inches the taproot branched freely and some of the branches were of considerable length, with many subdivisions Sometimes these deep branch roots enlarged after leaving the taproot, as did the more shallow ones A horizontal root was traced a distance of 3 feet, where it was still the size of a stalk of timothy The fibrous roots chiefly lay at a depth of 3 to 6 inches but many branches reached upward to the surface [44]

CHAPTER XXII

CARROT

The carrot (*Daucus carota sativa*) is either an annual or biennial plant. Early varieties seed the same growing season in which they are planted. Later ones produce only the whorl or large cluster of fern-like leaves the first year and extend the rough branching flower stalks to a height of 2 to 3 feet during the second season of growth. This fairly hardy, rather slowly maturing vegetable is common in most home gardens as well as in many market gardens. The "carrot" mostly consists of enlarged taproot but the upper portion develops from the hypocotyl and is a part of the stem.

Seed of the Chantenay variety of carrot was planted Apr. 24 in drill rows 18 inches apart. The seedlings were thinned to a distance of 5 inches in the row.

Early Development.—The first examination of root development was made June 10. The tops were 4 inches tall and consisted of five leaves each, the larger ones had blades 2 by 2 inches in outline and the average transpiring area, as determined by the aid of a planimeter, was only 12.5 square inches.

The plants were characterized by strong taproots 4 to 6 millimeters in diameter. These soon tapered to 1 millimeter in thickness, a diameter held throughout their vertically downward course. Depths of 27 to 32 inches were attained. Compared with other garden plants, the taproots were poorly branched (Fig. 61). No branches occurred in the surface inch of soil but to a depth of 6 inches they arose at the rate of five to six per inch. In the deeper soil branches were fewer and unevenly distributed. They varied in number from one to nine (average, three) per inch. Nearly all ran in a rather horizontal direction. They varied in length from 0.2 to 9 inches, the longest ones always occurring on the oldest portion of the taproot. Secondary branches, even on the oldest laterals, were not abundant. The last 6 to 9 inches of the taproot were entirely free of laterals. The poor branching and consequently relatively small absorbing area may be corre-

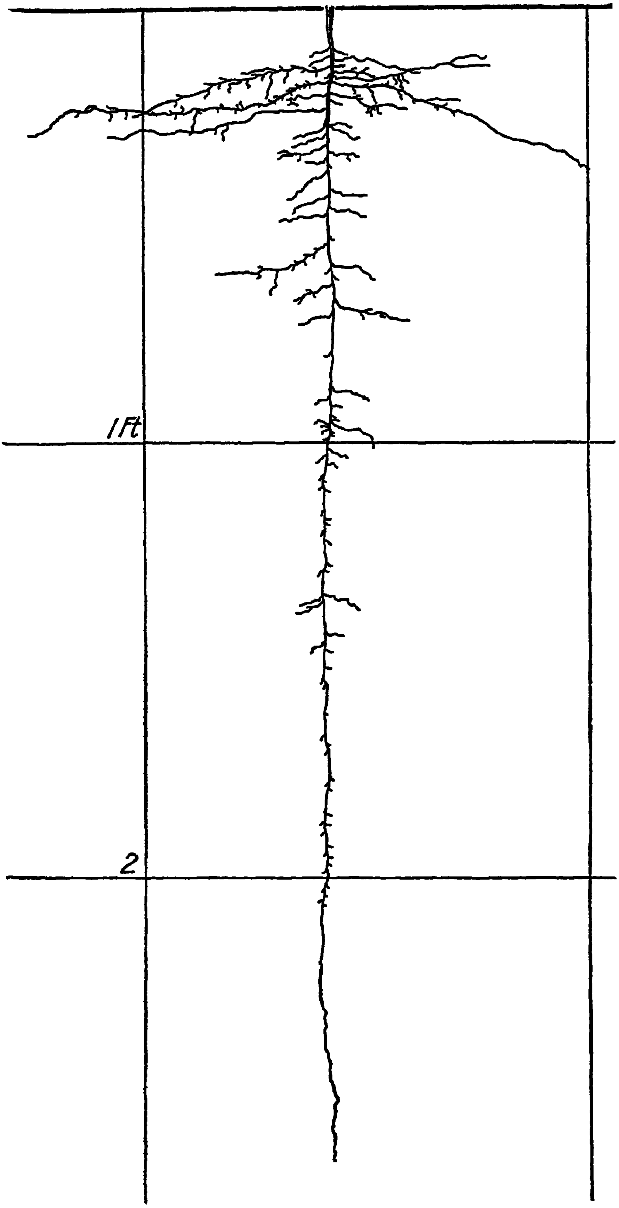


FIG 61 —Taproot system of a Chantenay carrot 47 days old

lated with the small transpiring surface afforded by the deeply incised leaves Even the root-hair development was much less

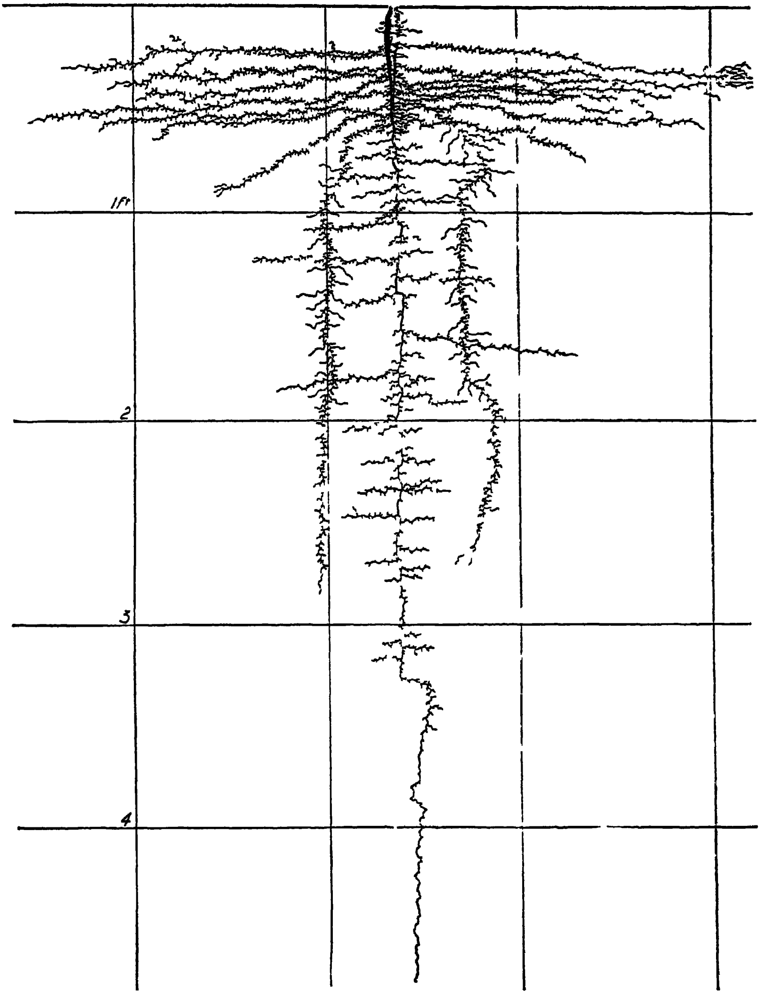


FIG 62 —Root system of a carrot a month older than that shown in Fig 61

pronounced than on many other garden plants The roots are very brittle

Midsummer Growth.—A month later, July 12, the plants had reached a height of 13 inches and attained a spread of 16 inches

The shoot had a thickness of ¾ inch near the base Each plant had about 14 leaves Many of these had blades 5 to 6 inches wide and 12 to 14 inches long Thus the transpiring and photosynthetic area had greatly increased

The fleshy portion of the taproot extended to a depth of 6 to 8 inches It had a maximum diameter of slightly more than 1 inch and tapered gradually at 8 inches depth to a thickness of about 2 millimeters In the deeper soil (below 18 inches) the taproot was only 1 millimeter thick Its course through the deeper soil was quite tortuous Abrupt turns and deviations of 0 5 to 2 inches from the vertical were frequent (Fig 62) Depths of 4 to 4 8 feet were usual

Only a few, short branches arose in the surface 2 inches of soil These were unbranched Between 2 and 9 inches in depth, however, 45 to 55 laterals originated Usually 16 to 24 of these spread horizontally for distances of 15 to 24 inches A few of those which originated deepest (5 to 9 inches) turned downward and frequently extended to the 2- to 2 7-foot level Although the other branches in this region of the taproot were shorter, thread-like, and poorly branched, these longer roots (about 1 millimeter in diameter) were clothed with laterals at the rate of 5 to 9, but sometimes 10 to 15, per inch They were 4 millimeters to 2 inches (rarely more) in length and most of them were unbranched A few of the main laterals that had been injured terminated in brush-like mats of rootlets Below the 9-inch level roots arose at the rate of three to four per inch throughout the course of the taproot except on the last 6 to 9 inches which were devoid of branches Below 3 5 feet these were short and unbranched Nearly all pursued a rather horizontal course Many short, unbranched or meagerly branched roots alternated with a few of greater length which were very well clothed with rootlets The relative lengths, degree of branching, etc are clearly shown in Fig 62 where a carefully selected root is pictured The older roots vary in color from tan to yellow Only the younger portions are white

Maturing Plants—At the final examination, Aug 12, plants of average size had 16 fully grown leaves and 4 to 6 partly developed ones Some of the older leaves had considerably deteriorated The fleshy portion of the taproot was about 8 inches long and 1 5 inches in diameter near the soil surface but less than ½ inch thick at the 8-inch level, the Chantenay being

a half-long, stump-rooted variety. The average number of branches at the several depths is shown in Table 15.

TABLE 15.—NUMBER OF LATERALS ORIGINATING FROM THE TAPROOT OF CARROT

Depth, inches	Small branches	Large branches	Depth, inches	Small branches	Large branches	Depth, inches	Small branches	Large branches
0–1	7	0	9–10	3	1	18–19	4	1
1–2	9	1	10–11	1	1	19–20	2	0
2–3	13	0	11–12	1	1	20–21	6	3
3–4	5	0	12–13	11	0	21–22	11	0
4–5	6	2	13–14	7	1	22–23	10	1
5–6	5	3	14–15	5	0	23–24	6	1
6–7	7	1	15–16	4	0	24–25	6	2
7–8	5	0	16–17	7	0	25–26	3	0
8–9	4	0	17–18	7	1	26–27	7	1

Thus on the first 2.3 feet of a taproot of average size approximately 20 large roots and 160 small ones had their origin. The large ones varied from 1 to over 2 millimeters in diameter. A few near the surface ran outward 12 to 18 inches and, like the network of shorter, smaller roots originating from the fleshy portion of the carrot, branched profusely and ended in the surface soil. But many of the larger roots, after pursuing a horizontal course for 1 to 2 feet (maximum spread 2.3 feet), turned downward. They then ran almost straight downward, ending in the 3- to 6-foot level. A comparison of Figs. 62 and 63 shows the characteristic development of these roots. At the earlier stage of growth (July 12) they had not reached their maximum spread. Moreover, only a few were utilizing the moisture and nutrients of the deeper soil.

Secondary branches on all of the roots were not only more abundant (4 to 13 per inch) but also longer (now 2 to 3 inches) than at the previous examination. Considerable variation occurred in the distribution of laterals. Some were 6 inches in length. Branches of the third order were nowhere abundant. An examination of the drawing shows that many new roots had arisen from the deeper portions of the taproot where they averaged 7 per inch. The average length, however, was only slightly greater than at the previous examination. The taproots were traced to their ends at depths of 6 to 7.5 feet. The roots were still growing vigorously. Judging from the development of such crops as parsnips (p. 224) and beets (p. 79) excavated in

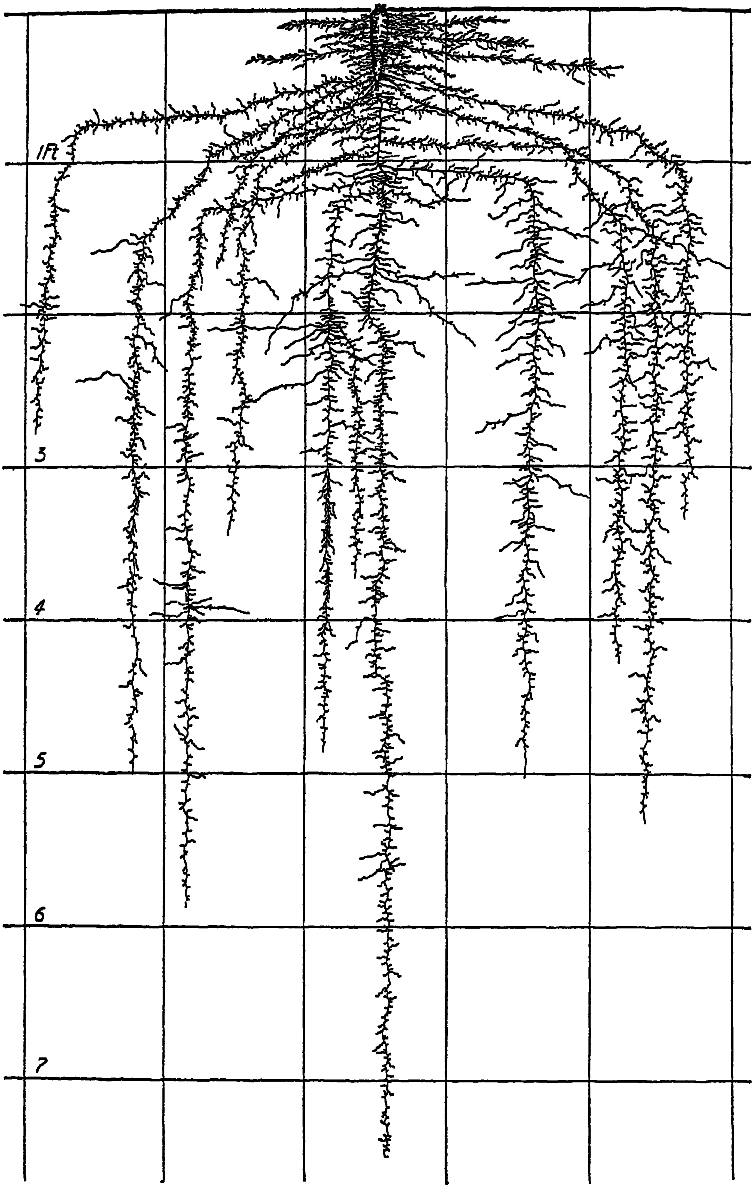


FIG 63.—Root system of carrot on Aug 12 The roots were still growing vigorously

September, it seems certain that the roots of the carrot reach a working level of 6 to 7 feet and a maximum depth at least of 10 feet.

Growth of Carrots during Winter and Spring.—Well-developed carrots of the Long Orange variety, with the fleshy taproots 2 inches in diameter, were left in the soil at Norman, Okla., at the end of the 1925 growing season. Because of late-summer drought there were only a few green leaves during August and September. Death of all or nearly all of the absorbing roots in the surface foot of soil resulted from the drought. Practically no growth either above or below ground occurred from the middle of August until after the September rains. By Dec. 3 there was a vigorous growth of leaves to a height of 8 inches and the roots also had made renewed growth. From the same areas on four sides of the fleshy taproot that had previously given rise to laterals, clusters of new rootlets occurred. These originated in clumps from the enlarged, bulging, meristematic areas, usually 5 to 25 occurring in a single cluster. From 500 to 1,500 were counted on individual plants. The roots were hairlike, a few millimeters to 7 inches in length and invariably pursued a horizontal course in the mellow, moist soil. Thus the older surface-absorbing system, only fragments of which remained intact, was being replaced by this newer one. The deeper and younger portions of the old root system were apparently functioning in a normal manner.

Further studies were made at the end of February. The plants had intermittently grown during the warmer winter weather, since soil moisture was very favorable (p. 19). The new roots, formed in the fall, were now 8 to 16 inches long. They had not deviated from their horizontal course. The larger ones were well furnished with numerous short laterals which greatly increased their absorbing area. Moreover, new laterals were developing on the old taproot to a depth of 2 feet as well as on the larger laterals near their place of origin.

On Apr. 16, when it became evident that the rapidly growing tops would need considerable room, the plants were thinned to 2 feet apart in the row.

Mature Plants.—By June 22 the plants had reached their maximum development. The numerous leafy stalks, 15 to 40 in number and 8 to 16 millimeters in diameter, reached heights of 30 to 42 inches. They were just ready to blossom. Roots were

exceedingly abundant in the surface foot of soil, on one plant there were 109 with a diameter of 1 to 2 millimeters and 430 finer ones in this soil layer. A maximum lateral spread of 30 inches was found. For example, one strong lateral, originating at a depth of 4 inches, ran obliquely outward and downward to a depth of 29 inches at a horizontal distance of 27 inches from the plant. Here it turned downward and ended 1 foot deeper. This illustrates the marked development of some of the new roots. Most of them, however, were shallower and shorter. The horizontal course of those arising within 2 to 3 inches of the surface and the more oblique direction of growth of those originating somewhat deeper were very characteristic. With its dense network of branches, this new root system rather thoroughly occupied the surface 12 inches as well as portions of the deeper soil. It greatly supplemented the activities of the deeper portion of the old root system.

The taproots reached a maximum depth of 55 inches. Strong, much-branched laterals occurred mostly in the second foot of soil. These spread 12 to 18 inches from the taproot and then often turned downward. Throughout its course below the first foot short laterals arose from the taproot at the rate of 4 to 12 per inch.

Summary.—Carrots are characterized by a strong, deep, well-developed taproot system. Plants with tops in the fifth-leaf stage have taproots 2.5 feet deep. Branching throughout is very poor. The greatest branching is in the surface 2 to 4 inches of soil where a few laterals extend horizontally 8 to 10 inches. During the following month the taproot grows 2 feet deeper. A fairly profuse network of horizontal branches extends from the lower half of the fleshy portion of the taproot 1.5 to 2 feet outward into the surface soil. A few major branches descend rather vertically, supplementing the absorbing area of the now better-branched taproot, to a depth of nearly 3 feet. About the middle of August, maturing plants have well-formed "carrots" from which fine roots arise in great abundance. These furnish an excellent surface-absorbing system near the plant. Many of the formerly horizontal laterals have turned vertically downward after reaching a maximum spread of 2.3 feet. They give rise to small laterals only but extend through the third and fourth and often the fifth foot of soil. Well-branched taproots reach the 7.5-foot level. The roots are still growing vigorously and undoubtedly extend much deeper.

When roots die from drought, they are replaced by multitudes of new ones of a very fibrous nature but often 1 5 to 2 5 feet in length A dry surface soil tends to promote a vigorous development of strong laterals from the deeper portions of the taproot

Other Investigations on Carrots—Carrots of the French Forcing and Long Red Altrincham varieties were examined in the middle of September at Geneva, N Y

> On both the taproot was small and soon tapered into a filament We traced it downward 16 inches, at which depth it was too delicate to follow further The horizontal roots apparently extended little more than 1 foot The fibrous roots chiefly proceeded from the taproot though a few started from near the base of the thickened part These extended both deeply and shallowly, some rising nearly or quite to the surface, while others apparently penetrated as deeply as did the taproot [42]

It seems clear in this case that the fineness of the root was an obstacle to its complete recovery by the method employed of washing away the soil

Carrots of the Long Orange variety were set out in the spring at the same station and examined late in September of the second year of growth The leading roots were found to extend quite as far as those in plants of the first year's growth The fibrous roots, however, appeared less numerous No branches from the horizontal roots extended upward to near the soil surface as was the case in both of the varieties grown for a single season The lower roots were developed to a greater extent than in those plants grown directly from seed [43]

At Saratov in southeastern Russia, the roots of the carrot have been traced to a depth of 40 to 52 inches Branching was very abundant in the plowed soil layer and the plant thus well adapted to absorb the water afforded by the summer precipitation At greater depths the branches were larger and occupied the soil rather thoroughly, being especially well developed where they occupied old burrows and earthworm holes [76a]

Investigators in Germany state that the roots of carrots are characterized by their great depth of penetration which was found to be about 5 feet The root system was much like that of the lettuce (p 324) in so far as the separate root branches penetrated rather vertically downward and did not spread widely But they differed in that adventitious roots were lacking in the carrot and branches of the first order furnished the means of

lateral spread These laterals were found to be rebranched in a manner similar to the lettuce [89]

Experiments in the vegetable gardens at Ithaca, N Y, where carrots were grown in a gravelly sandy loam are of interest The plants were grown in rows 18 inches apart The taproot and several other larger roots arising from the side of the carrot reached depths of 30 inches These roots produced almost countless numbers of branches which were themselves rebranched at least to the second order The soil directly beneath the plant was filled with roots to a depth of 25 to 30 inches A space 4 to 6 inches wide in the center between the rows was not so completely filled although at a depth of 4 to 8 inches many roots met and overlapped between the rows [152,159a]

Root Habit in Relation to Cultural Practice.—The amount of soil that must be pushed aside and the extensive development of roots in the surface soil helps to make clear the benefits of a deep, loose, mellow soil Such a soil is also beneficial in preventing the formation of a soil crust over the slowly germinating seeds and about the slowly developing plants The carrot has a delicate root system during its early stages of growth and one poorly adapted to penetrate stiff, hard soil Muck, a fine, loose-textured soil, is an ideal one for the growth of carrots and indeed for most root crops Since the plants grow slowly, they cannot successfully compete with weeds, hence the value of clean and thorough but shallow cultivation It has been shown at Ithaca, N Y, using both early and late carrot crops, that little or no benefit is derived from cultivation other than preventing weed growth Owing to the shading of the soil by the tops and the consequent lowering of soil surface evaporation, together with the thorough occupancy of the shallow soil by a dense root growth, soil moisture was not conserved by cultivation Plats where the weeds were kept out by scraping the surface usually had slightly less moisture than those repeatedly cultivated, but in some cases these conditions were reversed [152,158,159a]

For the best growth of the plant the usual spacing, 4 to 8 inches apart in rows 12 to 18 inches distant, is too close Competition between closely spaced plants results in considerable dwarfing When vegetable crops are crowded into a small area, garden practices, such as furnishing the plants with unusually large supplies of nutrients, conserving the water supply, and eliminating weeds, are employed to stimulate growth. Compe-

tition, however, is always severest where plants of the same kind are grown in close proximity All make the same demands for water, nutrients, and light at the same levels and at the same time The vegetable grower is concerned, however, with the best interests of the plant only in so far as they meet his needs By growing carrots thickly in favorably rich, moist, loose soil, he prevents the plants from attaining too great a size and secures an abundance of well-formed, succulent, medium-sized roots

CHAPTER XXIII

PARSLEY

Parsley (*Petroselinum hortense*) is a popular garden herb belonging to the carrot family It is a biennial or perennial plant grown for its leaves, which are used for garnishing, flavoring, and sometimes for salads Only the foliage of the first year is used The second year the plants produce stout flower stalks, 1 to 3 feet tall The plant develops slowly and is not ready for use until rather late in the summer

CHAMPION MOSS CURLED PARSLEY

Parsley of the Champion Moss Curled variety (*P hortense crispum*) was planted Apr 27 in drills 1 foot apart After germination and establishment the plants were thinned to 4 inches apart in the row

Early Development —By June 23, when the first examination was made, the shoots were over 2 inches tall and had a spread of about 1 5 inches Plants of average size had 5 leaves The small transpiring area of the much-dissected leaf surface was reflected in the rather poorly developed root system This consisted of a taproot and its branches Although 2 to 3 millimeters thick near the ground line, the main root tapered rapidly to a thread-like structure only about 0 5 millimeter or less in diameter Several taproots were traced to depths of 16 to 18 inches, the last 3 to 4 inches always being unbranched Practically no branches occurred on the first inch of root Between 2 and 8 inches, however, they averaged 9 per inch, varying from 3 to 16 in number Nearly all were horizontal, from 0 1 to 6 inches long, and many were unbranched Others were furnished with short branches only 0 2 to 0 5 inch long at the rate of 2 to 4 per inch At greater depths branching was even poorer and the laterals shorter and simpler (Fig 64) The roots were glistening white, fine, and delicate

Midsummer Growth —A second examination was made Aug 5 The plants averaged 4 inches in height, had a 9-inch spread of

tops, and those of average size were furnished with 22 leaves The taproots had now reached a diameter of 0 5 inch near the soil surface but tapered to 2 millimeters in thickness at the 1-foot level At 2 feet they were usually only 0 5 to 1 millimeter thick These thread-like roots pursued their tortuous course to maximum depths of 44 to 50 inches The last 8 inches were usually free from branches

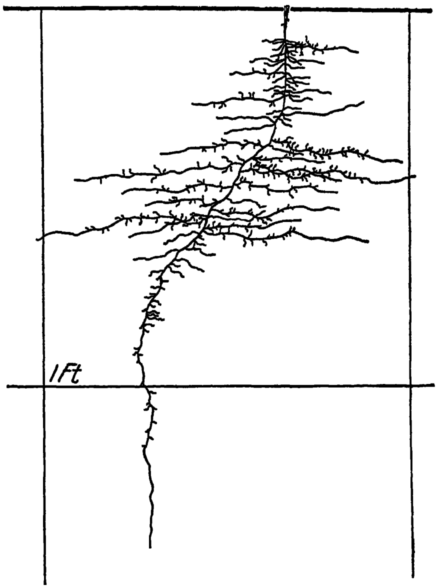


FIG 64 —Showing root habit of Champion Moss Curled parsley about 2 months old

At a depth of 2 to 12 inches 60 branches took their origin, sometimes 9 laterals arising from a single inch of taproot These were mostly only 4 to 6 inches long although 18 to 20 of the lot were 1 to 1 5 millimeters thick and reached lengths of 2 to 3 feet In general their course was at first outward and then obliquely downward, the lateral spread seldom exceeding 18 inches Rebranching occurred at the rate of 3 to 8 laterals per inch They were usually 0 2 to 2 inches long, and rebranched with short laterals at the rate of 3 to 5 per inch

Between 18 inches and 3 feet in depth horizontal laterals arose at the rate of 2 to 6 per inch They varied from 0 2 to 10 inches in length, 2 inches being an average The longer ones

were rebranched Below 3 feet branching was poorer (one to two branches per inch) and the laterals were short (average 0 1 inch) and simple The rate of branching, especially in the first foot, was always much greater on the distal ends of the laterals For example, the proximal half of the larger laterals usually had about six 0 2-inch laterals per inch, the distal half averaged 9 branches which varied in length from 0 2 to 3 inches In fact this difference in branching habit was very pronounced Many of the smaller laterals were dead and dry

The effect of soil structure and perhaps increased aeration were strikingly shown at the 24- to 30-inch level where the roots of some of the plants passed through the loose soil of a filled rodent burrow Here the rate of branching was distinctly greater, the branches much longer, and all were much more profusely rebranched

Compared to other crops, parsley has a rather meager root system, a fact undoubtedly correlated with its smaller transpiring area

Summary —Parsley is characterized by a taproot system with major branches originating only in the surface foot of soil The branches at first spread outward but soon turn downward so that the roots are confined within a radius of about 18 inches from the base of the plant Many attain depths of 2 to 3 feet The rather delicate taproot penetrates to the 4-foot level Like the main laterals, it is fairly well furnished with branches but these are mostly short although often well rebranched As a whole the root system grows slowly and does not ramify the soil so completely as do many other vegetable crops It should be stated, however, that the plants studied had not completed growth

EXTRA DOUBLE CURLED PARSLEY

Parsley of the Extra Double Curled variety was grown at Norman, Okla , in rows 3 feet distant The plants were spaced 1 foot apart in the rows The early growth and root development were so similar in every respect to that of the parsley at Lincoln that they require no separate discussion

Growth of both tops and roots practically ceased from the middle of July until the middle of September This resulted from the hot, dry weather Within a few days after the autumn rains, about the middle of September, growth was resumed. As

regards the roots, growth consisted of a renewal of laterals on the taproot and main branches as well as a renewal of growth at the tips of the roots already formed. The tops responded quickly to the increased absorption and by Oct. 1 leaf development was pronounced. This growth continued for a period of about 2 months and the tops increased in total spread from 7 to 13 inches, the leaves lying flat on the soil surface. After Dec. 15 growth was intermittent and although the plants were very hardy there was not much change in tops or roots until Mar. 15.

Resumed growth was initiated by the appearance of a few new rootlets from the taproot and its larger branches. But for the most part root development consisted of rebranching and extension of the roots already present. Above ground, erect leafy branches began to appear. By June 10 they had attained a height of 2 feet. The branching flower stalks were abundantly clothed with flowers and fruits.

By this time the taproot had increased to 1 inch in diameter. The 12 to 18 main branches from the first 8 inches of the taproot were 2 to 4 millimeters thick. Although many of the roots turned downward within 6 to 8 inches of the plant, a lateral spread of 42 inches was observed. The maximum penetration was 56 inches.

Root growth during the second season consisted almost entirely of renewed branching and growth of laterals rather than an extension of the older major roots into new soil. Thus the soil volume occupied by a plant was but little, if at all, increased, but the degree of ramification was much greater.

Other Investigations on Parsley.—Roots of parsley have been washed from a clay loam soil underlaid with a tenacious clay subsoil at Geneva, N. Y.

In this plant the root system was found to be extensive, and especially deep. On Sept. 17 the roots of a plant of the Common Curled and one of the Hamburg or turnip-rooted variety were washed out. Little difference appeared in the roots of the two sorts. In each the taproot was traced to a depth of 2.5 feet without coming to the end. At this depth the horizontal branches were frequent, being little if any more than ½ inch apart. At a depth of 18 inches the soil was pretty well filled with fibrous roots. The branches usually left the taproot in a horizontal direction and not infrequently grew slightly upward. At a depth of 4 inches below the surface a horizontal root was traced a distance of 2.5 feet. Many fibrous branches came to the surface.[44]

Root Habit in Relation to Cultural Practice.—The position of the upper portion of the root system so near the soil surface shows clearly that it would be greatly injured by any but shallow cultivation The slow growth both aboveground and underground makes it a poor competitor with weeds, hence the practice of clean, shallow cultivation throughout the growing season The closer spacing of parsley plants (usually 4 to 8 inches apart in rows 15 inches distant) than in many other garden crops is quite in accord with its smaller root system and less extensive tops

CHAPTER XXIV

PARSNIP

The parsnip (*Pastinaca sativa*), like the carrot, is a member of the parsley family It usually requires 2 years to complete the life cycle, *i e*, to produce the large, branching flower stalks which are 2 to 3 feet tall The plant is grown as an annual for its long, cylindrical, tapering, fleshy taproot It is a slowly growing, long-season, very hardy plant The roots are frequently left in the soil over winter where they are unharmed by freezing Although the parsnip is a very common vegetable, it is of rather minor importance commercially

Parsnips of the Hollow Crown variety were planted Apr 24 in rows 18 inches apart After the seedlings were well established, they were thinned to 5 inches distant in the row

Early Development —By June 18 the plants had a height of 4 to 5 inches and a top spread of about 4 inches Each plant was furnished with four leaves The total leaf surface was 19 square inches

The extent of the root system was quite marked considering the rather meager development of the aboveground parts Very slender taproots penetrated vertically downward except for small twists and turns Depths of 19 to 28 inches were found on the several plants examined Figure 65 shows the characteristic branching habit, abundant laterals, both short and long, extending outward in a nearly horizontal direction on all sides of the taproot Usually no laterals arose in the surface inch of soil, and long ones arose only at a soil level deeper than 3 inches

The average lateral penetration in the surface foot was somewhat less than 3 inches, but the maximum lateral spread was 9 inches In the second foot the branches were younger and shorter, often only 0 2 inch in extent The ends of the taproots as well as the laterals, were quite unbranched In fact many of the shorter laterals were simple The longer ones were furnished with short branches (usually only 0 2 to 1 inch long) mostly at the rate of 3 to 5 per inch These, however, were confined to the

older parts and were only rarely rebranched In regard to the number of main laterals, these varied from 4 to 13 per inch of taproot, many counts giving a mean of 8 per inch They were

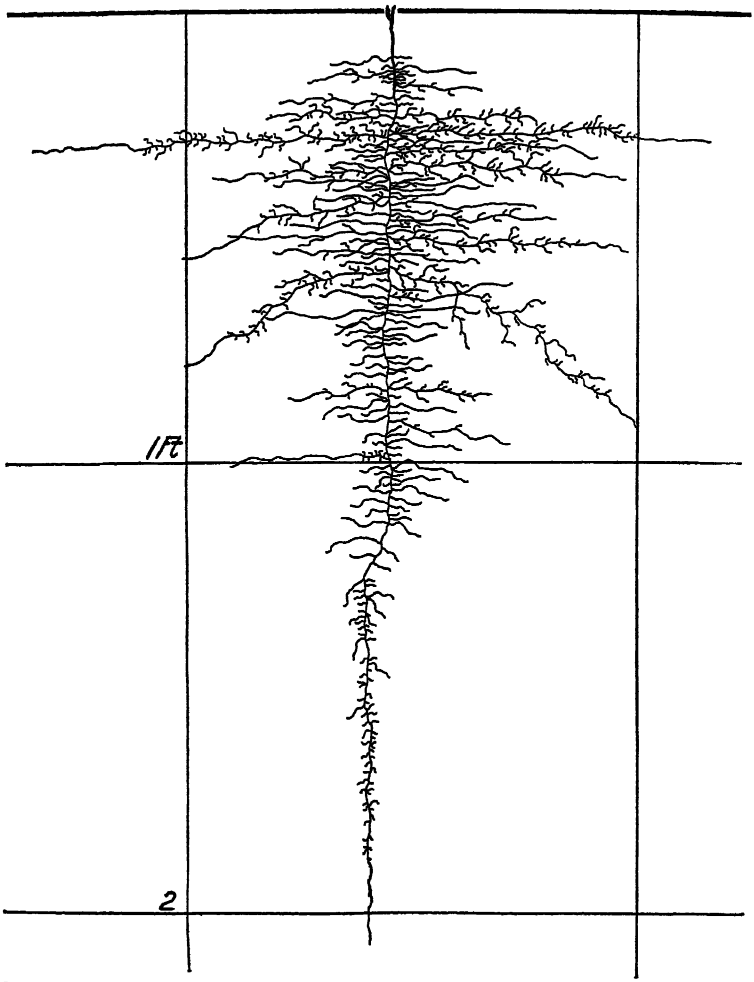


FIG 65—Taproot system of a young parsnip of the Hollow Crown variety This plant was only 8 weeks old

very fine and uniformly distributed The entire root system of shining white roots was rather simple and was excavated with relatively little difficulty

Midsummer Development—During the following month the plants made a good growth They were again examined on July 14 The shoots were over ½ inch thick at the base and about 15

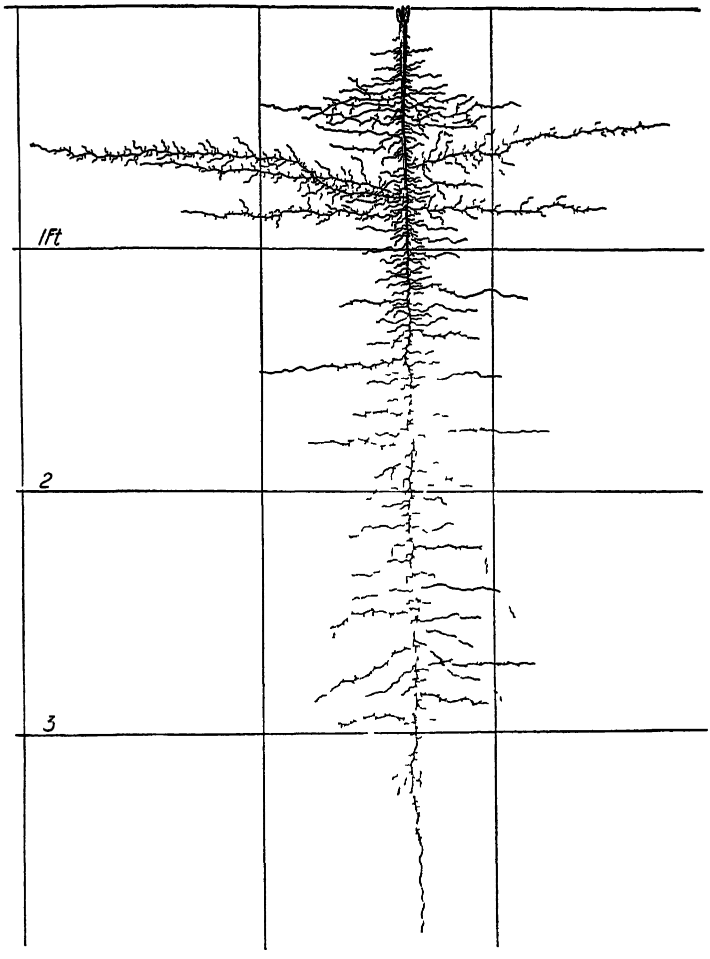


FIG 66—Parsnip root system on July 14 The plant was about 1 month older than that shown in Fig 65, both root and top had made a vigorous growth

inches tall They had a total spread of 6 to 12 inches The leaves were about 12 inches long and 7 inches wide

The formerly thread-like taproot now had a thickness of 7 millimeters near the soil surface and 2 millimeters at a depth of 1

foot, below which it tapered to 1 millimeter and then to less than 1 millimeter in thickness Aside from slight curves it penetrated almost vertically downward to depths of 40 to 46 inches The general root plan had not changed (Fig 66) As before only relatively few short branches occurred in the first 3 inches of soil Below this level they became longer, those originating at depths of 5 to 12 inches sometimes extending 9 inches (maximum, 22) rather horizontally away from the taproot In the still deeper soil even the longest branches seldom exceeded 6 inches

Most of the branches were quite fine, usually only four to six per plant reaching 1 millimeter in thickness Occasionally, however, one of the finer branches enlarged near its end to this diameter The rate of branching averaged eight per inch in the surface foot (aside from the surface 3 inches) and somewhat less in the deeper soil Thus the rate of branching had not increased over that of the preceding examination As before, moreover, numerous simple, short branches were intermixed with the longer ones These were usually only 1 to 3 inches long Only the longer branches were supplied with rootlets They were mostly 0 1 to 1 inch long and seldom exceeded two to four per inch in number The roots were fine and white in color, except that the oldest ones were yellowish They were nearly always poorly rebranched The horizontal position of the laterals is characteristic

Aside from absorption by a few branches which extended more widely, the plants were securing their entire nutrient and water supply from soil volumes about 3 feet deep and less than 1 foot in any of their diameters This limited root area is probably correlated with the character of the tops

Plants in Autumn —At the final examination, Oct 5, the plants averaged 17 inches in height Each had from 14 to 28 leaves and a spread of tops of approximately 21 inches The large leaf blades were about 12 inches long and 7 inches wide

The taproots had increased greatly both in thickness and depth Near the soil surface they were often 2 inches in diameter but tapered to 0 5 inch at a depth of 1 foot At 2 feet they were still 5 millimeters thick and 3 millimeters at 3 feet but below 8 feet less than 0 5 millimeter in diameter At the 8-foot level roots were common and a maximum penetration of 9 feet was determined In the surface 10 inches of soil frequently 20 laterals over 1 millimeter thick and 70 smaller ones took their

origin Thus apparently a few new laterals had grown from this portion of the taproot Many of the smaller roots were short, others were 20 to 30 inches long Most of them were unbranched or nearly so The larger ones extended more widely, sometimes to distances of 3 feet These were clothed with branches 0 2 to 2 inches long at the usual rate of five to eight per inch Only the longest were rebranched and even these were not rebranched profusely

In the deeper soil, to 4 feet, branches were somewhat fewer and in general did not extend so far laterally No large branches were found below 4 feet But even below 8 feet two to four laterals originated from 1 inch of the shining white roots The characteristic odor of the fleshy parsnip root was observed even near the root ends

A habit noted on a number of plants was that of the division of the taproot at a depth of about 3 feet into three to five almost equal parts These often ran outward 2 to 4 inches and then, turning downward, extended more or less parallel to depths of 8 to 9 feet Branches on these were like those on the taproot, hence the absorbing area was considerably increased Where this division occurred, other major branches sometimes arose below the 4-foot level

As a whole the root habit had changed very little from that of the preceding examination The most important differences were the great increase in depth (from 3 7 to 9 feet) and the accompanying growth of laterals in the deeper soil The original branches, of course, had considerably extended their absorbing area but nowhere was a profuse network of rebranched laterals evident Just how much the maturing plant depended upon this newer portion of its absorbing area and to what degree the older portion had become non-functional is an important problem awaiting solution

Growth of Roots during Winter and Spring.—Studies of the root system at Norman, Okla , early in December and again Feb 28, showed that the parsnip, unlike the carrot (p 211), had made no new root growth A month later the tops showed considerable new development and simultaneously a number of new roots began to grow from the crown near the surface These roots were of little importance, however, in increasing the absorbing area But small roots on the larger branches in the surface foot of soil also showed renewed growth By increase

in length and by the development of abundant laterals, the efficiency of the root system was greatly enhanced

Mature Plants—Mature parsnips of the Improved Hollow Crown variety were also excavated in Oklahoma, May 30, during their second year of growth The plants had been thinned to 2 5 feet apart in the 36-inch rows at the beginning of the second season Cultivation throughout had been done with a mulching

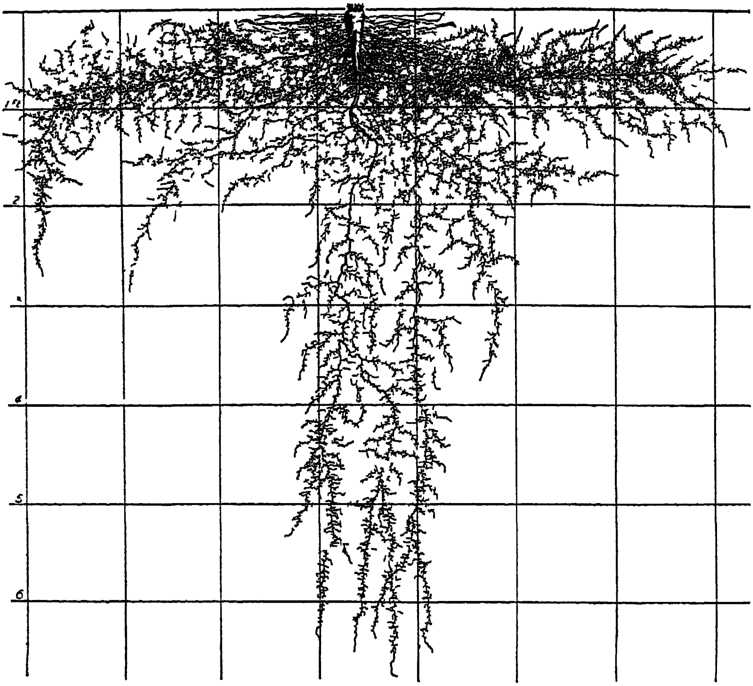


FIG 67—Mature root system of Improved Hollow Crown parsnip The plant was excavated at Norman, Okla, on May 30 of the second season of growth Many of the finer laterals are not shown

fork and did not exceed 2 inches in depth The plants were 4 feet tall and in addition to the main stem each had three to four branches from the crown The main stalks bore numerous branches and flowering was profuse on all The leaves were still green and thriving

The strong taproot was 2 5 inches in diameter at the crown and tapered gradually to 5 millimeters at a depth of 2 feet Seven strong laterals, 3 to 5 millimeters in diameter, originated on the

first 16 inches of the taproot. In addition there were 58 laterals at least 1 millimeter in diameter and numerous clumps of 5 to 14 finer rootlets. A lateral spread of 4 feet and a depth of over 6.5 feet were attained. The thorough occupation of the surface soil as well as the extent and degree of branching in the deeper soil, is well shown in Fig. 67. For the sake of clarity many of the smaller rootlets are not shown. Water and available nutrients were obtained from a very large soil volume.

Summary.—The parsnip, like the carrot, has a very extensive taproot system. When only four leaves have developed, the taproot reaches the 2-foot soil level and is well furnished with laterals throughout. These are slow, however, in developing secondary rootlets. The surface soil is not well occupied during the early life of the plant. A month later the taproot extends almost to the 4-foot level. Except for a few horizontal laterals, 12 to 22 inches long in the second 6-inch level, the taproot is quite uniformly branched to a depth of 3 feet. The branches are mostly horizontal, 1 to 6 inches long, and poorly, if at all, rebranched. In October, large, leafy plants have taproots 2 inches thick and 8 to 9 feet long. The number of main laterals in the surface foot has been somewhat augmented. A lateral spread of 3 feet has been attained. Branching is not profuse. In the deeper soil branches are fewer and less widely spreading. No large branches occur below 4 feet. Thus the absorbing system is not so well developed as in the carrot and many other vegetable crops. Plants grown in sandy loam have a similar habit except that they are not so deep but somewhat better branched.

Renewed growth of roots in spring occurs synchronously with that of tops. Growth during the second season consists in part of the development of numerous long roots just below the soil surface but largely of the extension and profuse branching of the smaller laterals already found the preceding season. Strong taproots, 6 to nearly 7 feet long and now profusely branched throughout, fill the soil. A wonderful network of absorbing rootlets ramifies the surface 16 inches of soil to a distance of 3.5 feet on all sides of the plant. At greater depths a column of soil 18 inches thick is also well occupied.

Other Investigations on Parsnips.—At Geneva, N. Y., the root system of the same variety (Long Hollow Crown) was excavated in the middle of September. The taproot was found to taper very slowly after the first few inches in depth. It was traced to 30

inches "beyond which it was too delicate to follow "[43] Branching occurred throughout its length One of these, at a depth of 2 feet, was followed a distance of 7 inches through very stiff clay Fibrous roots in the upper layers of soil were very numerous but short, the longest ones appearing to extend only about 14 inches from the main root "Considering the proportion of the roots that lie deep in the soil, the parsnip is a deeply rooting plant "[43]

Root Habit in Relation to Cultural Practice.—A study of the slow germination and growth of the parsnip, together with its early development of delicate rootlets, makes clear why a deep, rich, open soil is best It will not bake and form a crust over the seeds or about the seedlings Branched, crooked, and misshapen roots, common to shallow and lumpy soils, will not be formed under such conditions Early, shallow cultivation to prevent weed growth and possibly to conserve moisture is desirable Later the vigorously developing roots, extending widely through the surface soil and deeply into its moist layers, are able more successfully to make the best of their surroundings and even to compete with weeds By growing plants thickly, *i e*, 4 to 8 inches apart in rows 14 to 18 inches distant, sufficient space is insured and enough competition afforded to develop roots of desirable size

CHAPTER XXV

SWEET POTATO

The sweet potato* *(Ipomoea batatas)* is a prostrate, trailing, perennial herb, grown as an annual for its enlarged, fleshy roots It is a member of the morning-glory family, of tropical origin, and one of the leading crops of southern United States It is also grown to a considerable extent in the North It rarely forms seed in the United States and is propagated vegetatively Methods of propagation are pertinent here since they are concerned with root development

Methods of Propagation—Tubers of moderate size are placed in a hotbed and shallowly covered with loose earth or sand Sprouts soon develop from adventitious buds which are usually located near the base of former, fibrous, lateral roots After these have grown up through the soil covering, more sand or soil is added to promote the development of a good root system When the shoots are 3 to 5 inches high, they are removed and set in the field In this manner two to five crops of slips may be taken from one root [37]

When the plants are set into the field, they are watered like tomato or cabbage transplants if the soil is dry Frequently, the roots are dipped into a thin paste made of mud and water This not only prevents them from drying in the process of planting but also causes the soil to adhere to them Pressing the soil firmly about the plantlets to establish a good contact is essential The plants are sometimes propagated by root cuttings placed directly in the field

Sweet potatoes are also propagated, especially in the South where the growing season is longer, by cuttings made from the ends of the vines Slips are planted early in the season, and when the vines begin to run, cuttings are made In making the cutting 8 to 12 inches of the end of the vine is used All of the leaves are removed except the partially grown ones near the tip The cutting is shallowly buried in the soil in the field in a more or less

* The potato is discussed in "Root Development of Field Crops"

horizontal position and the soil firmly packed about it Only a small portion of the tip is permitted to extend aboveground Such vine cuttings have several advantages over slips They produce roots more nearly uniform in size and shape and are free from some of the sweet-potato diseases that are carried from the seed bed to the field on the slips They are also cheaper to produce and afford a yield which is quite as large or larger than from plants grown from slips [156]

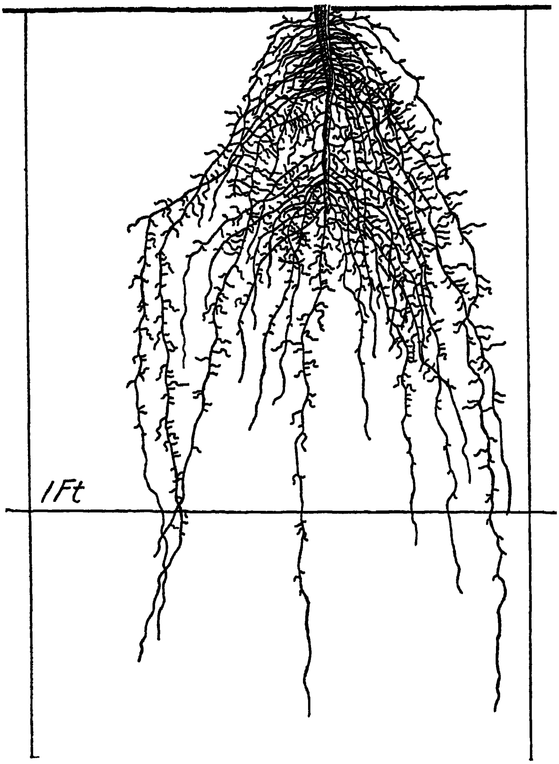


FIG 68—Root system produced from a root cutting of the Yellow Jersey sweet potato 23 days after transplanting it into the field

Sweet-potato plants of the Yellow Jersey variety were transplanted into the garden on June 1 The plants were set 15 inches apart in rows 4 feet distant

Early Growth—At the time of the first root excavation, 23 days later, plants of average size had 30 to 35 leaves with blades that varied from 1 to 2 5 inches in length and width Many

branches had grown from the original root cuttings. A typical case will be described.

The transplanted root, which was 4 millimeters thick and 5 inches long, gave rise to 71 branches. These originated rather uniformly throughout, beginning just beneath the surface of the soil. Their general course was outward and downward, nearly all running obliquely at angles of 45 degrees or less from the old root (Fig. 68). Many were only about 1 inch long, others reached a maximum spread of 4 inches and a depth of 17 inches. This depth was not exceeded by roots which penetrated rather vertically downward from their origin near the base of the cutting. None of these fine, rather tough, glistening white roots were more than 1 millimeter in diameter, even at their origin, and they were usually much less. When injured they exuded a white sap. Laterals were fairly abundant, about six per inch, thread-like but rather firm. They grew at right angles from the main roots. Usually they were unbranched, but a few of the longest had the beginnings of branchlets. The whole rapidly growing root system, because of its light color, stood out in striking contrast to the dark soil. The long, glistening white, unbranched root ends were very characteristic.

Midsummer Growth.—One month later, July 25, root development was again investigated. Typical specimens now had 12 to 19 prostrate branches varying in length between 1 and 4.5 feet. Frequently, there were about 8 of the longer ones. In addition some new vines less than 1 foot long were found. The older, basal leaf blades were 2.5 by 3 inches in size, the younger ones near the ends of the branches were about half as large. Some of the vines were rebranched. As many as 400 to 450 leaves were found on individual plants, thus presenting a rather large transpiring and food-making surface.

A thorough study of the underground parts showed that they had developed in proportion to the tops. The roots ramified the soil 2 to 3 feet on all sides of the plant and penetrated to a working level of 2.6 feet. A maximum depth of 41 inches had been attained. A study of Fig. 69 gives a fair idea of root development and distribution.

Each plant had 12 to 16 large roots 1.5 to 4 millimeters in diameter and many smaller ones, all of which originated from the transplanted cutting. Some of the larger roots had become quite fleshy (diameter 0.2 to 0.5 inch) throughout 2 to 4 inches of their

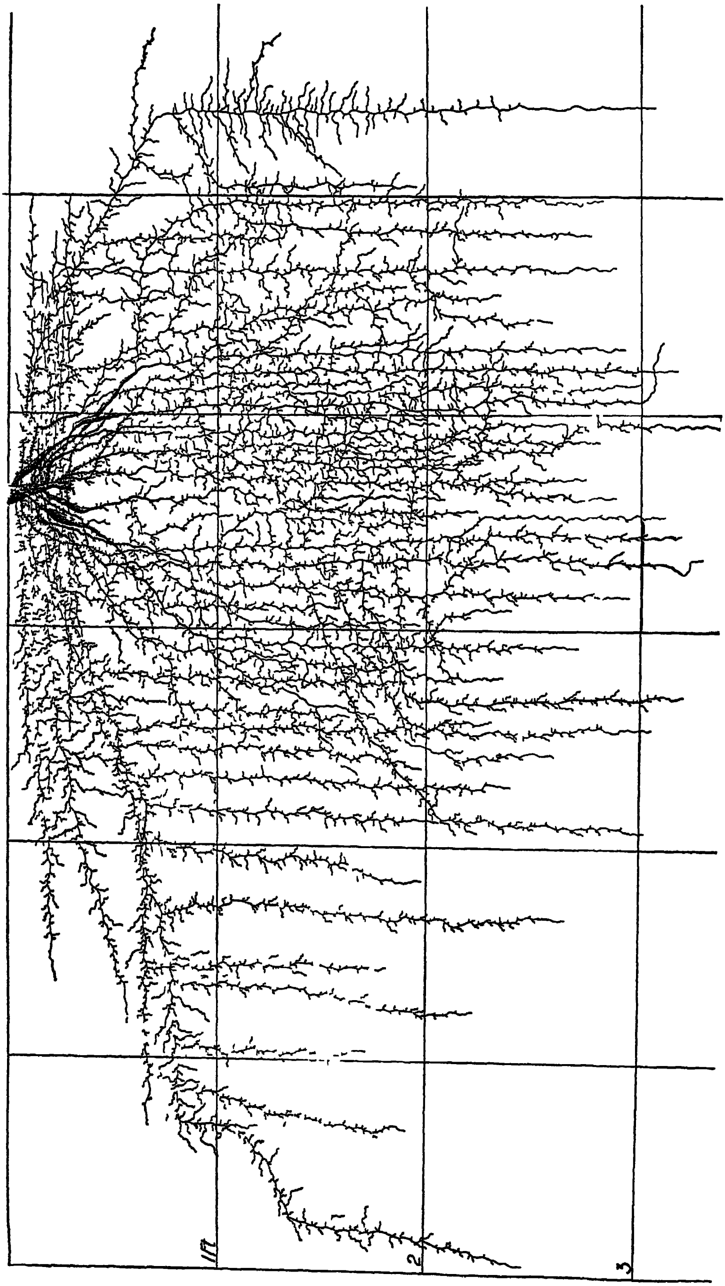


FIG 69 —Development of sweet-potato root system on July 25 It is 1 month older than that shown in Fig 68

course In the surface inch of soil there arose numerous horizontal laterals only about 1 inch long and entirely unbranched Others ran horizontally or nearly so 2 or more feet, branching freely but ending in the surface 6 to 8 inches of soil Still others ran obliquely outward and downward in such a manner that when they reached a lateral spread of 1 5 to 2 5 feet they were still within the surface foot These roots frequently gave rise to numerous, long, vertically penetrating branches which reached depths of 2 to 2 5 feet For example, one main lateral, which finally ended at a depth of 21 inches but 40 inches horizontally from the base of the plant, gave rise to 11 roots of this type Still other main roots turned more obliquely downward, some descending almost vertically and filled the soil beneath the hill They branched widely and ended near the working level Some of the large laterals from these more vertical roots spread obliquely in the deeper soil and ended, but more usually turned downward, 6 to 17 inches horizontally from their origin The usual spreading of branches, whether vertical, horizontal, or intermediate, at wide angles (often at right angles) with the branch from which they originated is characteristic

Branching of the laterals was very similar throughout An average rate of 3 to 8 branches per inch was determined There were seldom fewer than 2 and sometimes as many as 12 Length of branches was more variable Those that clothed the longer roots, whether of the first or second or sometimes the third order, usually ranged between 0 2 and 2 inches in length Longer or shorter ones were much less frequent These laterals were only rarely rebranched As shown in the figure, however, the soil was well filled with roots Both tops and roots were growing vigorously This was clearly revealed underground by the glistening white root ends, the last 2 inches of which were usually unbranched

Mature Plants —A final examination of the root habit was made on Oct 3 The vines had made an extensive growth, frequently 12 occurring on a single plant Many of them had a length of 14 feet and gave rise to 175 leaves Since the leaf blades were approximately 3 5 inches in length and width, a very extensive transpiring surface was presented The average spread of a single vine was about 20 inches and an individual plant covered nearly 200 square feet of soil surface

There were about 12 "potatoes" per hill, the largest being 2 inches thick and 5 inches long Most of these fleshy roots

extended downward rather obliquely and were usually found in the surface 6 to 9 inches of soil. More than 1 foot of the large roots extending beyond the swollen portion was also yellow in color. The thick root cutting to which these "potatoes" were attached was only 3 inches long. It gave rise to 8 to 15 absorbing roots that extended outward rather horizontally. Many of the roots that extended downward from the root cutting were dry in the hard, fissured soil layer which occurred at a depth of 21 inches. They penetrated far beyond this depth, however, usually to the 4-foot level. These roots were furnished with laterals at the rate of 3 to 5 per inch, some of which extended outward 2.5 feet.

The fleshy portion of the roots gave rise to three to eight roots per inch. These were 8 to 12 inches long, pursued an almost horizontal course, and were rebranched at the rate of three to six short branches per inch. In addition about three large laterals 3 millimeters in diameter arose from each "potato." These usually extended horizontally 1 to 1.5 feet and then, turning downward, reached depths of 4 feet or more. The main roots, of which the "potatoes" were the enlarged parts, were 3 to 4 millimeters in diameter. They usually extended downward. But at the base of nearly all of the "potatoes" one or two large horizontal laterals also arose. These ran rather horizontally 10 to 18 inches and then penetrated downward to 4 feet or more. Branching on these roots and on the main roots was very similar. Most of the branches were 1 to 6 inches long and furnished with short laterals. On the main roots, in addition to a few short rootlets, to a depth of 2.5 feet, there were one or two roots per inch that extended almost horizontally 6 to 8 inches and then ran downward to about 3 feet. These were rebranched at the rate of three to five short branches per inch.

Between depths of 2 to 3 feet the branches on the roots were more sparse and usually partly dried. These occurred at the rate of two to four per inch, being quite unbranched and only 1 to 2 inches long. But below the 3-foot level, where the soil was more moist, the branches were more numerous, longer, and in good condition. The maximum depth of penetration was 69 inches; the working depth 51 inches.

In addition to the roots described the stems gave rise at their nodes, and sometimes on the internodes, to an enormous number of roots. As many as 10 to 15, usually in 2 rows, arose from a

single node, and there were 3 or 4 such clumps per foot of stem Not infrequently a node would give rise to a single root These single roots were profusely furnished with laterals, 1 to 1 5 feet long, which ran mostly horizontally, were rebranched to the third order, and formed a very intricate root network These main roots were usually only 1 millimeter in diameter but many were swollen to 5 times this thickness for a distance of 3 to 6 inches Most of them extended almost vertically downward but some ran obliquely outward several inches and then turned downward in their course A working depth of 40 inches was ascertained although some were found 10 inches deeper The roots which arose in clumps were very profusely branched in the surface 6 to 8 inches of soil As many as 12 to 18 branches per inch were common They extended horizontally 2 to 10 inches Those that exceeded 1 inch in length were rebranched at a similar rate with rebranched rootlets 1 to 2 inches long In fact, the soil was literally filled with the profuse network of these adventitious roots and their numerous branches Undoubtedly they were carrying on much of the absorption for the plants This was indicated by their fresh color and more turgid condition when compared with the main root system

The most striking character about the root system of the sweet potato is the intricate network of roots that underlies all of the stems and leaves This undoubtedly promotes the rapid growth and wide spreading of the stems since the source of water and nutrient supply is not far removed from the leaves

Summary —The sweet potato is propagated vegetatively by slips developed from root cuttings, by cuttings made from the ends of vines, and sometimes by root cuttings themselves Plants grown by the last method rapidly develop an extensive fibrous root system Three weeks after transplanting, roots are abundant from the soil surface to a depth of 17 inches Nearly all run obliquely downward, the lateral spread not exceeding 4 inches A month later the vines are 1 to 4 5 feet long The roots extend from just beneath the soil surface to a working depth of 2 6 feet Laterally, they run 2 to 3 feet They are well branched throughout Mature plants have vines 14 feet in length In addition to about 12 fleshy roots per plant, the attenuated portions of which branched widely and penetrated deeply, there are usually an equal number of extensive roots of small diameter These penetrate far outward and downward, mostly to a depth of 4 feet Long

sublaterals are common and shorter branches very profuse. A network of roots ramifies the soil from its surface to a depth of 51 inches. Abundant, profusely branched roots arising from the nodes of the vines penetrate deeply and add materially to the absorbing area. Thus the soil under the widely spreading vines is completely filled with a dense, absorbing network of roots.

Root Habits of Certain Sweet-potato Relatives.—The root habits of certain relatives of the sweet potato are of interest for comparison, especially since some are noxious weeds. The hedge or great bindweed (*Convolvulus sepium*) is a perennial plant that propagates freely from a rootstock, the numerous roots penetrating deeply. In the moist subsoils of eastern Nebraska a depth of 5 to 7 feet is usually attained. The small or field bindweed (*Convolvulus arvensis*) propagates from creeping roots. Under a surface area covered with the vines of this species, the soil is thoroughly occupied with roots. In eastern Nebraska depths of penetration of 15 to 17 feet are not uncommon. It is of interest that the rhizomes and root offshoots of these plants vary in depth with the compactness of the soil. In very hard soil they may occur almost entirely in the surface 2- to 10-inch soil layer. In mellow, cultivated soils they are much deeper and frequently most abundant at the 6- to 18-inch soil level.[79] The widely spreading and deeply penetrating root habits of the morning-glory have been confirmed by studies in Colorado.[119]

A greater root extent, however, is attained by a plant more nearly related to the sweet potato, the bush morning-glory (*Ipomoea leptophylla*). This species is common in sandy soil of the semiarid, central portion of the United States. It is a perennial with an enormously enlarged taproot, which is often 1 foot or more in diameter and tapers to 1 inch or less only at a depth of 4 to 6 feet. This enlarged portion of the taproot not only furnishes an enormous reservoir for food but also a storehouse of water upon which the plant may draw during a period of drought. The taproots extend to great depths, at least 11 feet and probably to twice this depth. Throughout their course they are profusely branched. Many of the branches penetrate obliquely outward or downward. Others pursue a nearly horizontal course. Many have an enormous spread, the roots running outward to distances of 15 to 25 feet or more. The surface foot of soil, as well as the 10 feet below it, is literally filled with the glistening white, brittle branches of this remarkable root system.[167]

The root habits of the wild ancestors of cultivated plants, so far as the plants are known, would make an interesting and valuable study The object sought in cultivating plants is usually to produce a growth of some of their parts, whether flower, seed, fruit, leaves, stem, or root, that is unnatural to the species in its native habitat Undoubtedly in so doing other parts of the plant are also greatly modified The modern varieties of vegetable crops have become accustomed to growing in soil especially prepared and liberally supplied with everything the roots need In fact, the plants are unable to fully develop in soils of moderate fertility Surely this has brought about great changes in the root habit

Root Habit in Relation to Cultural Practice.—A number of interesting and important root relations are concerned with the growing of sweet potatoes as a result of the cultural condition imposed upon this plant of wild ancestry

Soils and Fertilizers —Since the sweet potato is a tender plant of tropical origin, it grows best in an easily warmed soil For proper growth of the fleshy roots soil should not be plowed too deeply In such an instance, there is a tendency for the roots to grow slender and too long On very rich soil the crops produce too much vine growth and the "potatoes" are likely to be too large and rough In heavy clay soils they are also likely to be rough and irregular in shape but in lighter, easily moved soil they are usually more uniform in size and smoother Hence a light, moderately rich soil, such as a sandy loam with a clay subsoil, is perhaps best, although under irrigation light sandy loam and coarse sandy soil are most suitable [122]

Fresh manure causes a rank growth of vines and the development of large, rough roots

> Well decomposed stable manure applied in the row is beneficial in producing maximum yields but when manure is used in the drill, the surface of the sweet potato is more likely to be disfigured with black marks known as scurf and spoken of as "soil stain," "mottling," "rust," etc This spoils the appearance of the sweet potatoes and reduces their keeping qualities [31]

It has also been shown that nitrogen in excessive quantities tends to produce long "potatoes"[132]

Water Relations —It has been observed in New Mexico that if sweet potatoes are kept well irrigated and the surface soil moist,

a larger crop is produced and the "tubers" are nearer the surface of the ground than where the soil is allowed to become too dry In the latter case, the roots tend to grow deeper in the soil There is a development of the root system, seemingly at the expense of the crop and the "tubers" are found quite deep in the soil [37] This, of course, increases the difficulty and expense of securing them and they are much more apt to be bruised in the process, thus increasing subsequent losses from decay

The plant roots so deeply and extensively that, once the roots are well established throughout the soil, it endures drought much better than most vegetable crops In fact, it will produce a fair crop in semiarid regions where most vegetable crops will not thrive at all Under irrigation in California good growth and yields have been observed where by midsummer there was no available soil moisture nearer than 20 to 24 inches from the soil surface [122] The roots, however, are intolerant of poor aeration resulting from a wet soil Hence the common practice of setting the plants on ridges often 8 to 15 inches high [122, 143, 178] The ridges should be as low and flat as the drainage conditions will permit for the higher and narrower the ridges the more rapidly water is lost The effectiveness of this method, of course, depends upon the season, but experimental evidence shows that the yields are often increased

Cultivation, Rooting of Vines—The practice of thoroughly preparing the soil by repeated cultivation before the plants are set is an excellent one since it avoids a later disturbance of the roots in cultivation It is the common practice also to maintain a surface mulch and to keep the weeds out by shallow cultivation at least until the vines cover the ground Usually at each cultivation the soil is gradually moved toward the rows But the vines must not be covered with soil, otherwise they will develop roots early in the season and hinder the best development of the main roots The rooting of the vines between the rows later in the season does not reduce the yield [31] Many gardeners continue cultivation later by turning the vines first to one side of the row and then to the other during the process This prevents the development of adventitious roots, as already described, and it often prevents the full development of the crop For example, in Georgia the yield of the Pumpkin Yam variety was decreased 107 bushels per acre [143] Similar results, with a decrease varying from 5 to 126 bushels per acre, have been

obtained in Louisiana and Arkansas [111] The extensive development of adventitious roots greatly reduces the distance water and nutrients must travel to supply the vines with these materials essential to food manufacture On the other hand a certain amount of the energy of the plant is expended in growing these roots During dry years, especially, preventing the vines from rooting would seem to be especially injurious to the plants [178, 143]

Pruning and Spacing —Although the effect of pruning the vines has not been studied in connection with root development, it would seem that pruning would retard it Indeed, this has been found to be the case in regard to the fleshy portion of the roots, although some growers believe that reducing the growth of foliage stimulates root development For example, in New Mexico, hills pruned back to 12 inches in diameter yielded 6,012 pounds per acre, those pruned back to 24 inches produced 8,690 pounds per acre, and the yield where no pruning occurred, was 16,520 pounds [37] Similar results were obtained in Georgia Unpruned plants produced 201 3 bushels per acre but plants pruned weekly throughout the season to a length of 2 feet produced only 104 9 bushels [143]

Spacing of the plants seems to be determined in practice largely by the spreading of the aboveground parts and the ease of cultivation To afford room for the widely spreading vines, the plants are widely spaced A planting distance of 12 to 18 inches apart in rows 3 to 6 feet distant is usual Under these conditions root interlacing occurs to a marked degree and the soil is thoroughly occupied

Harvesting —It is of the utmost importance that the roots be removed from the soil soon after the leaves have been killed by frost since water accumulates in the roots This results from the cessation of transpiration in consequence of the destruction of the leaves The "potatoes" may safely be kept in the ground until mature or until the leaves have been injured by frost During the latter part of the period of growth and up to the time of the death of the vines, the root is characterized by a high starch and a low sugar content The choice of the time of harvesting is not a matter of the maturity of the roots but is governed by other factors With the termination of the flow of materials from the vines, the carbohydrate transformations characteristic of sweet potatoes in storage are inaugurated These are principally the changes of starch to sugars [53]

Summary—The root habits of sweet potatoes are closely related to cultural practice in many ways Chief among these are the selection of the proper kind of soil and its thorough preparation before the plants are set, the effects of the application of fertilizers and water of irrigation upon the root habit, the relation of the roots to drought and soil aeration, manner and time of cultivation in relation to the root system and the rooting of the vines, the effect of pruning the stems on root development, spacing of the plants in the field, and, finally, physical and chemical activities of the root in relation to time of harvesting

CHAPTER XXVI

TOMATO

The common garden tomato (*Lycopersicon esculentum commune*) is a coarse, rankly growing, much-branched, annual plant, although in its native home in tropical America it is a perennial The tomato is nearly always found in the home garden as it is one of the most common, most profitable, and dependable of crops Truck growers and market gardeners extensively cultivate the tomato which in importance ranks third among truck crops [8] It probably is the most important of canned vegetables Being a tender crop it is grown from plants started in specially prepared seed beds several weeks before the time of planting in the garden or field This permits an earlier ripening of the fruit and a longer season for growth Since the yield is closely correlated with the length of the bearing season, the advantages of this practice are obvious [17]

Early Root Development and Its Relation to Transplanting — When tomato plants are grown from seed, they develop a strong taproot which, under favorable conditions for growth, may reach a depth of 22 inches in 3 weeks This growth has a rate of 1 inch a day On plants of the John Baer variety, the taproots were uniformly branched to within 2 inches of the tip The rate of branching in the first 6 inches was 10 to 12 laterals per inch, at greater depths the number varied from 6 to 8 per inch At this time the plants were approximately 4 inches tall and had about 4 leaves each It is clear that such plants could be set into the field only with difficulty Hence the practice of transplanting one or more times before the plants are finally set into the field Transplanting or potting of seedlings tends to modify the natural taproot system into a more or less fibrous one, due to the injury to the taproot The change in the root system is really very profound (Fig 70)

Much time is saved by setting out well-grown plants rather than starting the crop in the field from seed A desirable plant for setting in the field is 6 to 8 or even 10 to 12 inches tall, with

thick, tough stem, plenty of dark-green leaves, the crown bud developed, and a large fibrous root system which will enable it to stand transplanting[17, 121, 120] (Fig 71)

Tomato seedlings of the John Baer variety were transplanted to the garden May 16 They were set 4 feet apart and the stems were allowed to grow on the ground without pruning

On June 11, the time of the first excavation, the plants were 8 to 12 inches tall and had, on an average, 10 compound leaves The leaves, of 5 to 13 leaflets, were about 5 inches long and presented a transpiring surface of 94 square inches The stem of the plant at the ground line was more than ¼ inch in diameter

FIG 70—Typical root system of a tomato grown from seed sowed in the field (right) and one that has been transplanted (left) This illustrates the pronounced change brought about by transplanting the seedlings (*After J T Rosa*)

The tomato was characterized by a taproot which tapered gradually from a width of 10 to 13 millimeters near the soil surface to only 2 millimeters at a depth of 6 inches As a result of transplanting the taproots, if unbroken at this depth, were usually curved sidewise or even upward On plants where the taproot was sharply curved often several large laterals arose either from the point where the curving occurred or directly above it In fact this phenomenon of root branching has been repeatedly observed on numerous species of plants both cultivated and native Usually one of the main roots penetrated quite verti-

cally downward and a maximum depth of 2 feet was reached Although profuse branching occurred in the surface soil at depths greater than 2 inches, below 8 to 10 inches the thread-like main root was poorly branched (Fig 72) Usually 4 to 6 short branches (none over 1 5 inches long) per inch of root arose. The last 4 to 7 inches of the glistening white, fairly tough, main, vertical roots were unbranched

In the surface soil, usually below 2 inches, roots arose in great profusion The adventitious root system, *i e*, roots arising from

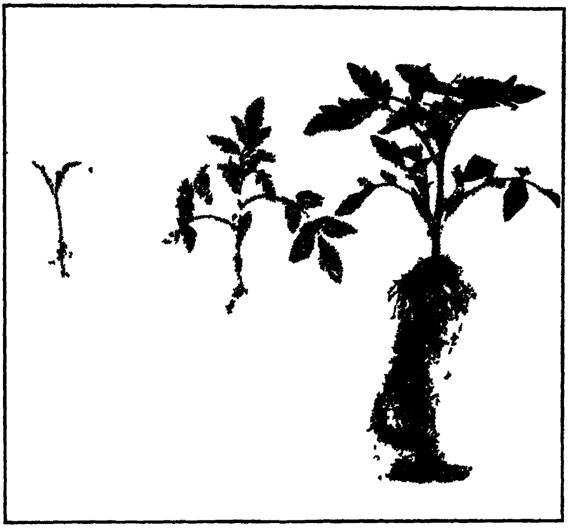


Fig 71 —Three tomato plants from seed of the Baltimore variety planted at the same time The one on the right was transplanted to rich soil in a 4-inch clay pot when it was about the size of the plant on the left The center plant, with spray material on the leaves, was transplanted to soil in a cold frame The plant on the left was not removed from the original seed bed Note the comparative root systems The tomato on the right is a desirable plant for setting into the field (*After Brown, Purdue, Ind, Agr Exp Sta, Bull* 288)

the buried stem, was making a vigorous growth In the seedling stage the young roots grow out from the stem in distinct vertical rows which correspond with the position of the fibrovascular bundles within the stem But after the plant becomes larger and older they arise from all sections of the stem below the soil surface From 18 to 33 laterals clothed each inch of taproot Like the adventitious roots, nearly all of these took a horizontal course Although most of them were only 1 inch or less in length, many were 6 to 9 inches long Thus the surface soil for nearly 1

foot on all sides of the plant was thoroughly ramified with rootlets Even beyond, to a maximum distance of 2 feet, larger laterals were found A few had reached their greatest spread from the taproot and started to turn downward Only rarely did a root pursue a downward course in proximity to the taproot

In regard to branching, laterals were profuse Usually, however, branches were short (2 to 5 millimeters) until the roots had extended 2 to 4 inches from the taproot Thereafter they ranged in length from 0 3 to 2 inches and usually occurred at the

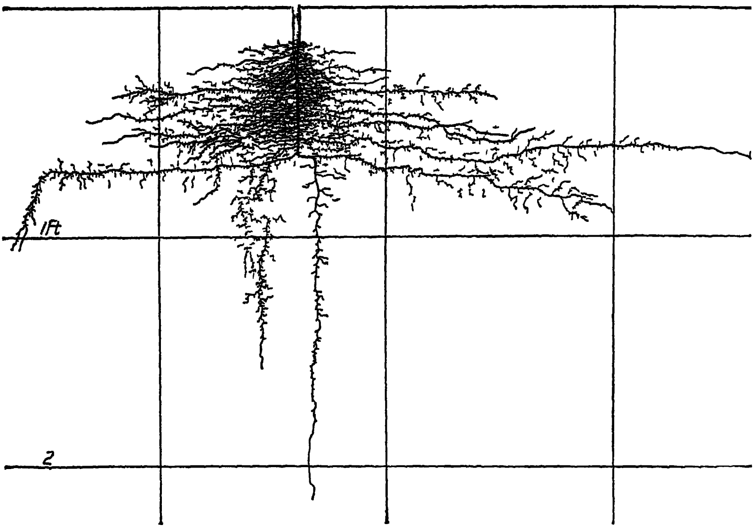


FIG 72—Root system of John Baer tomato about 4 weeks after transplanting into the field

rate of 5 to 10 branches per inch Occasionally branches 4 to 6 inches in length were found Many of these thread-like laterals were quite profusely rebranched with short sublaterals These glistening white, rather tough, fibrous roots and their branches were, at this stage of development, almost or quite confined to the surface 2 to 10 inches of soil It was here that the plant was getting its abundant supply of water and nutrients for rapid growth

Later Growth.—A second examination was made 1 month later, July 11 The plants now had an average height of 19 inches, a spread of tops of about 2 feet, and each was furnished with 6 to 11 branches The average total leaf surface at this

time was approximately 12 square feet The plants were blooming profusely and had also developed a few green fruits, the largest scarcely exceeding 1 5 inches in diameter

The stem was 0 8 inch in diameter near the soil surface and tapered slowly to a rather stubby root end of the enlarged portion at 6 inches in depth, the taproot having been broken in transplanting As at the earlier examination, the prominent part of the root system consisted of very abundant laterals Many of these had now extended outward to 2 or more feet, mostly in the surface 9 inches of soil Then turning obliquely downward, they had reached depths of 3 to more than 3 5 feet The soil beneath the plant was fairly well occupied with other laterals which turned rather obliquely downward without spreading, and with long branches from the more horizontally spreading ones (Fig 73)

The number of laterals was very large For example, one plant had 16 small laterals in the first inch of soil, there were 41 small branches and 3 large ones (1 millimeter or more in thickness) in the second inch, 30 small laterals in the third inch, 19 small and 5 large roots (1 to 5 millimeters in diameter) in the fourth inch, 24 small and 5 large branch roots in the fifth inch, 16 small ones in the sixth inch, none in the seventh, and 6 small ones in the eighth inch of soil At greater depths there arose 3 to 8 small laterals per inch of taproot The young and short rootlets in the surface inch were poorly branched But branches occurred in great numbers on all of the deeper ones Very frequently the larger roots gave rise to branches 6 to 24 inches in length, and, in fact, some were as long as the main laterals These branched again, thus greatly extending the absorbing area Laterals only 0 3 to 2 inches in length, and frequently furnished with sublaterals, were common almost throughout the entire extent of larger roots Although they varied in number, 4 to 8 per inch (but sometimes 15) were common Below 2 5 feet the branches were shorter and frequently less abundant on these younger portions of the roots The last few inches of the rapidly growing roots were free from branches A working depth of about 3 feet and a maximum penetration of 49 inches were found The rather tough roots were of a light-tan color except the youngest portions which were white

Summarizing, the root system of a tomato plant of average size filled the soil on all sides of the plant to 2 to 2 5 feet and to a depth of over 3 feet Thus more than 65 cubic feet of soil were

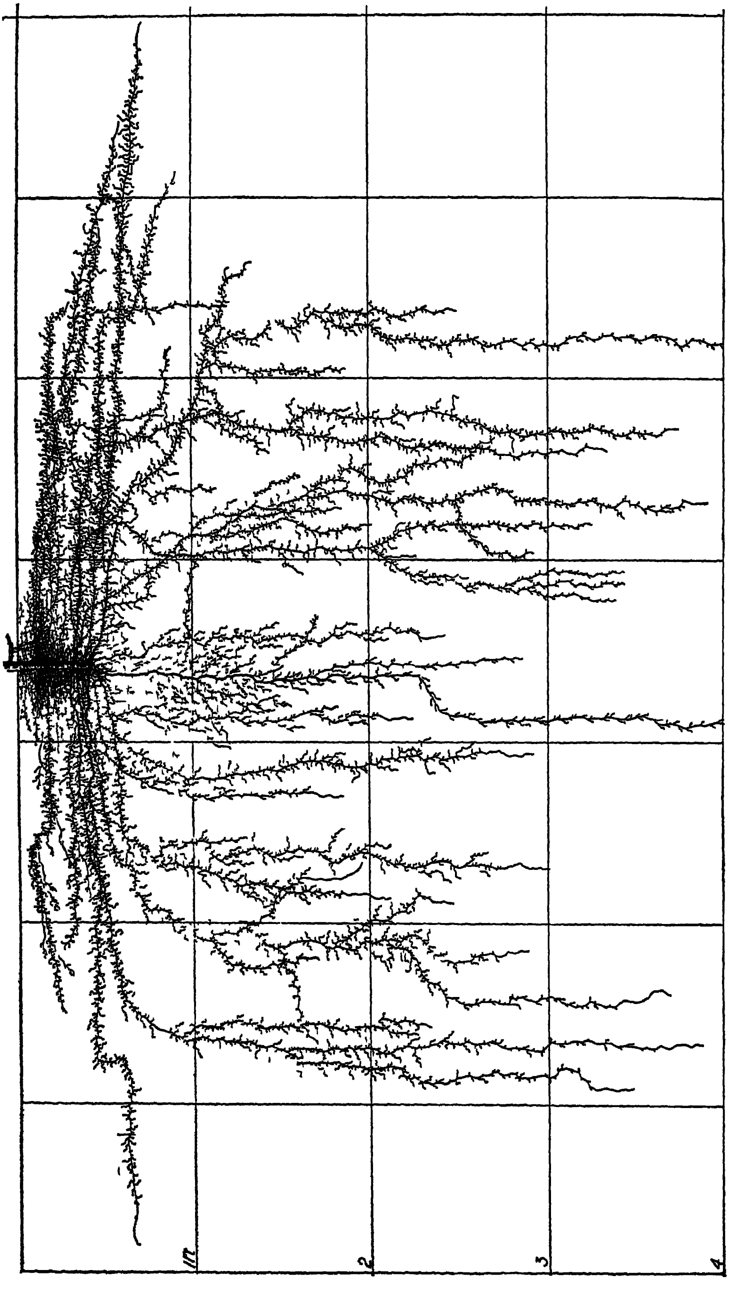


Fig 73 —Tomato on July 11 It is 1 month older than that shown in Fig 72

already ramified and the roots were rapidly extending downward into new territory

Maturing Plants.—By Aug 13 the well-developed plants had a top diameter of about 4 feet The number of leaves varied from 400 to nearly 500 per plant The leaf surface exposed to water loss was very large A plant, for example, with only 294 leaves had a leaf surface of 69 square feet (Fig 74) The plants bore fruit abundantly

Roots arose in great numbers from the base of the stems. About half of them were only 1 to 4 inches long and unbranched

Fig 74 —A fully grown tomato plant with a surface area of 69 square feet A very extensive root system is necessary to supply sufficient water and nutrients for such a large top

Larger ones were furnished with 5 to 7 short branches per inch throughout their older portions Perhaps the general root habit may best be visualized by a study of the behavior of some typical major laterals One of these, arising at a depth of 3 inches, grew away from the base of the plant to a distance of 3 feet, where at a depth of 11 inches it turned rather vertically downward and penetrated to a depth of 45 inches From a diameter of 6 millimeters at its origin it tapered to 2 5 millimeters at the 2 5-foot level but it maintained a diameter of 1 millimeter to its end At 5 inches depth it gave rise to two large branches, which ran parallel in their downward course, finally reaching the 4-foot

level Another primary lateral, also originating at a depth of about 3 inches, forked dichotomously when 5 inches from the taproot One branch descended nearly vertically to 4 feet, the other ran rather horizontally 3 5 feet in the surface foot of soil and, then turning downward, also penetrated to the 4-foot level During its horizontal course the latter gave rise to 11 large branches which were found to extend to depths of 3 to 4 feet One of the largest primary branches, 7 millimeters thick, originated at a depth of only 4 inches It ran horizontally 20 inches where it branched into 3 equal parts All pursued a horizontal course The first forked again at 52 inches from the base of the plant, one branch turning downward immediately, the other extending 1 foot farther before entering the deeper soil The second, after pursuing a devious course in the surface foot of soil through a distance of 8 5 feet, was 5 5 feet from the taproot when it turned downward and penetrated to 4 5 feet The third had a very similar course

When it is stated that a single plant of average size possessed 15 to 20 branches somewhat similar to those described and almost countless smaller ones, the really enormous absorbing area of the tomato begins to be apparent Moreover, branching was very profuse throughout Branches occurring at the rate of 8 to 10 per inch of rootlet were common These varied from unbranched laterals 0 5 inch or less in length to branches 2 feet long and rebranched to the fourth order Sometimes the ultimate branchlets were 0 3 to 1 inch in length Even a single, main lateral forking and reforking, giving rise to branch after branch, most of which were long and penetrated deeply and all clothed with an intricately branched network of rootlets, furnished an enormous absorbing area Even the roots at the working level (42 inches) and in fact to near the maximum depth (52 inches) were exceedingly well branched In addition, numerous roots arose from many of the prostrate branches even at 6 to 8 inches from the taproot Dense clusters of roots 6 to 12 inches long were furnished with 12 to 20 rootlets per inch Thus a soil volume with a surface area of at least 80 square feet and a depth of 3 5 feet—280 cubic feet of soil—was thoroughly ramified Many roots extended more widely (maximum, 5 5 feet) and some even penetrated more deeply

Summary.—Tomato plants are started in especially prepared seed beds, transplanted once or twice, and then set into the field

The strong taproot, which may develop at the rate of 1 inch per day, is injured and a dense fibrous root system promoted by transplanting. Plants of the John Baer variety, scarcely 1 month in the field, reach a depth of 2 feet and a maximum lateral spread of 24 inches. Most of the exceedingly numerous, much-branched, horizontal laterals occur between 2 and 10 inches in depth. The adventitious root system develops rapidly but the surface soil is still free from rootlets. A month later when the top has a transpiring surface of 12 square feet, the roots are very extensive. Many of the strong laterals, all of which arise in the surface 10 inches of soil, spread horizontally 2 or more feet and, then turning downward, penetrate into the third and fourth foot of soil. Others pursue a horizontal course throughout, ending 3 feet or more from the base of the plant. Still others run obliquely downward, usually one strong root assuming the rôle of a taproot. The main roots often give rise to very long laterals which also penetrate deeply. All of the roots are extremely well branched, and the 2 feet of soil on all sides of the plant are well filled with roots to the 3-foot level. The adventitious root system thoroughly ramifies the surface soil.

Mature plants have a transpiring surface of 70 to 100 square feet and a wonderfully extensive root system. Usually 15 to 20 major branches spread widely (maximum, 5.5 feet), have very numerous large branches, which usually penetrate deeply, and finally, turning downward, extend into the third, fourth, and sometimes the fifth foot of soil. In addition there are almost countless smaller main laterals. All are so profusely furnished with masses of much rebranched rootlets that the absorbing area is extremely intricate and extensive even beyond the working level of 3.5 feet. A very large soil volume, beginning just beneath the soil surface, is very completely ramified with rootlets.

Other Investigations on Tomatoes.—A tomato plant was examined at Geneva, N. Y., Aug. 13. The greater part of the roots appeared to extend horizontally and were about 8 inches below the surface. The horizontal roots were traced to a distance of 24 to 30 inches from the base of the plant.

From this it appears that the plant drew its nourishment from a circle about 4.5 feet in diameter or from an area of about 16 square feet. A single root was traced downward to a depth of 2.5 feet. The taproot was clothed with a multitude of fibrous roots to the depth of 8 inches, where it separated into many branches.[42]

Root development of the Bonny Best tomato was carefully studied at Ithaca, N Y The plants were grown in a loam soil The spacing of the plants in the field was 2 by 3 feet for those to be pruned and trained and 4 by 4 feet for those not to be pruned They were set in the field from 4 × 4 inch paper bands Twenty days later "the greatest depth reached by any of the roots was 12 inches and the greatest lateral growth was from 15 to 16 inches Most of the roots were found in the surface 6 inches of soil at this time When the plants were full-grown, some of the roots had

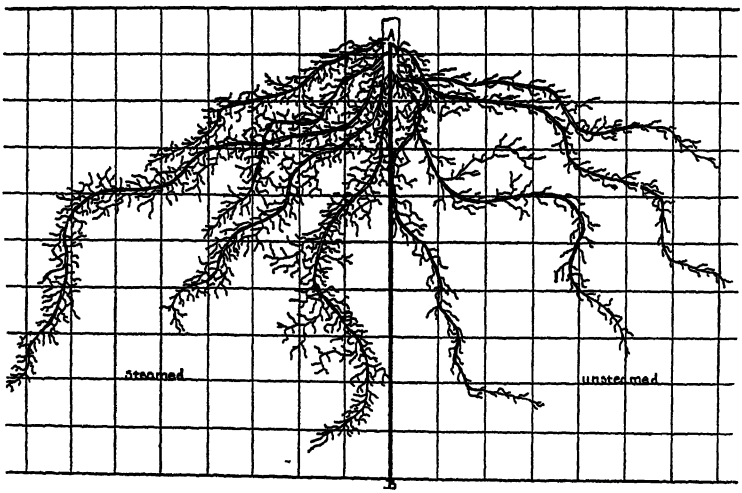


FIG 75 —Tomato plant 78 days old Line *A-B* is a paraffin layer separating the steamed (left) and unsteamed (right) soil (*After Ora Smith, Iowa State Agr College, Ames, Iowa*)

reached a depth of 3 feet and a lateral spread of from 3 to 4 feet Studies made on both the trained and the untrained plants show a considerable difference in their respective root systems With the trained plants, which were pruned to a single stem and tied to stakes, very few roots were found in the centers between the rows, while with the unpruned plants there were many more roots in the centers The centers between the rows of trained plants were practically without roots at all depths, while with the untrained plants, in the surface 6 inches of soil there were many roots in the centers between the rows, although these rows were 1 foot farther apart than those of the trained

plants. The unpruned plants also had more roots running down into the soil than did the pruned plants. Measurements of the foliage showed that the unpruned plants had about five times as much leaf area per plant as had the pruned plants. The root growth in general was proportional to the foliage growth."[159a]

Observations on the growth of tomato plants have also been made in Germany.[89] In the main, plants were grown in containers but the root systems of plants growing in the open were also washed from the soil. The taproot, at first quite distinct, became, at greater depths, so delicate that it was difficult to distinguish it from the mass of laterals. The adventitious root system developed relatively early. The branches pursued a horizontal or oblique course and were branched much like the main root. Plants only 8 inches tall had a depth of 4 feet. The roots grew at the rate of over 1.2 inches per day. Some were 5 feet long. They had developed branches to the third order. The rate of branching was profuse. For example, in an area 41 by 13 inches 1,427 rootlets were found. The root system of the tomato studied rather thoroughly occupied a cubic volume of soil slightly over 4 feet in each dimension.

It has been found in Iowa that steaming the soil, for the purpose of sterilizing it, has a marked effect upon the root system of tomatoes. It has been repeatedly shown that the tops of plants grown in steam-sterilized soil have a greater amount of growth and this has been found to be related to a more extensive root system.[129] In the Iowa experiments[139, 140] Bonney Best tomatoes were planted in composted bluegrass sod grown on a fertile loam soil. This was placed in wooden boxes 18 inches in length and width and 10 inches deep. The experiments were so arranged that steamed soil occupied either the upper or lower half of the box or one-half of the box throughout its entire depth. The other half was filled with similar but unsteamed soil. The soils were separated by a wax seal. Great differences were found in size, extent, and fineness of roots. As shown in Fig. 75, roots in the steamed soil were larger, more numerous, and the root system had a more fibrous nature than those grown in unsteamed soil. Plants in the steamed soil had a larger and heavier root system in proportion to tops than those in the unsteamed soil. Two laterals of the same length were selected from the two sides of a box and the following data procured.

Soil treatment	Plants 47 days old			Plants 78 days old		
	Number of roots, second order	Number of roots, third order	Number of roots, fourth order	Number of roots second order	Number of roots, third order	Number of roots, fourth order
Steamed	56	21	2	60	35	12
Unsteamed	39	10	1	43	21	3

In every case the number of roots of second, third, and fourth orders growing in the steamed soil exceeded the number in the check soil In one instance there was an increase of 160 per cent It was further ascertained that between the ages of 47 and 78 days the increase in the number of roots is almost entirely in the third and fourth orders, few roots of the second order being produced in this period As maturity and fruitage approached, the root system made no further significant growth Why the tops of plants grown in steamed soil are larger is now clear The finer and smaller roots, clothed with root hairs, furnish the absorbing surface for the plant This part of the root system is greatly increased by steaming the soil Steaming the soil makes more plant nutrients available It has the same effect upon vegetative growth as the addition of well-rotted manure and the effect is provisionally attributed to some of the organic products of decomposition effected by the steam [128] It also brings about changes in texture, moisture content, and movement of water Perhaps the manurial effect is the most important factor but all may aid in producing a more fibrous, more extensive, and hence more efficient root system

Other investigations have shown that, when tomatoes are grown in a soil with low water content, there are more roots in proportion to tops than where an optimum water content is maintained Similarly plants grown in soils low in nitrates had fewer roots in proportion to tops than when an optimum nitrate content was maintained [97]

Experiments on Root Distribution, Cultivation, and Water Conservation —Tomatoes of the John Baer variety were grown in 1926 to determine the effect of deep tillage on root distribution and its relation to water and nitrate content of the soil The plants were grown in two plats of which the rows (five in each plat) were 40 feet in length and 4 feet apart When transplanted

on May 3, they were set 4 feet distant in the rows. These plats, which adjoined those of the cabbage (p. 109), were given exactly the same treatment as the cabbage in regard to cultivation, *i. e.*, one was hoed 3.5 inches deep and the surface of the other was scraped. The uncropped area between the cabbage plats was used as the check.

The root system was examined on June 19. It agreed in every way with those already described. The tomato had more roots in the surface 3 inches of soil than the cabbage. More roots per plant (below 3.5 inches) were found on the tomatoes in the deeply hoed plat. Where the roots had been cut as a result of hoeing, the remaining portion of the root developed more branches throughout, but especially from near the injured root end (Fig. 76).

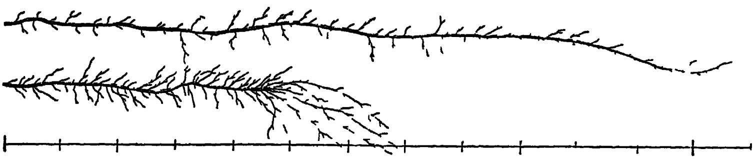


FIG. 76.—Representative surface roots of tomato under two types of cultivation. The upper root shows normal development in the surface soil layer. The lower one has been cut by deep cultivation. This resulted in a great increase in branching. Scale in inches.

Late in July it was found that the roots extended to within 0.5 inch of the soil surface just beneath the base of the plants in both plats. Otherwise in the scraped plat the roots often penetrated to within 1 to 1.5 inches of the surface but the deeply hoed plats only rarely had roots in the surface 3.5 inches of soil. It was found that roots of the plants adjacent to the uncropped area between the plats, which was 10 feet wide, extended almost across it so that even the center of this area was drawn upon for water and nutrients.

An examination of Table 16 shows that, notwithstanding the dry season, on this lowland area there was sufficient moisture available for growth, a fact substantiated by the excellent development of the plants. The amount of water in the uncropped area in excess of that of the cropped one, otherwise similarly treated, ranged from 0 to 3 per cent until the roots became extensive. After July 2 differences were much greater, often 4 to 8 per cent. The moisture relations in the deeply hoed and uncropped plats were, after the roots became widely spread, 2 to 7 per cent more

favorable in the uncropped area. The excess moisture in the deeply hoed over the scraped plat was consistently greater in the surface 6 inches after June 25, and often 2 to 5 per cent higher. At greater depths differences were also rather consistently in favor of the deeply cultivated plats. These differences may be due in part to the loose soil retarding water loss directly from the surface and perhaps largely, in the surface 3½ inches, to little absorption from this soil layer.

TABLE 16.—APPROXIMATE AVAILABLE WATER CONTENT, i.e., AMOUNT ABOVE THE HYGROSCOPIC COEFFICIENT, IN THE SEVERAL PLATS AT LINCOLN, NEB., 1926

Date	Depth, feet	Uncropped, scraped soil	Cropped, deeply hoed soil	Cropped, scraped soil	Excess water of uncropped over cropped, scraped soil	Excess water of uncropped over cropped, deeply hoed soil	Excess water of cropped deeply hoed over cropped, scraped soil
June 9	0.0–0.5	10.7	12.4	10.7	0.0	−1.7	1.7
	0.5–1	15.0	14.5	15.4	−0.4	0.5	−0.9
June 17	0.0–0.5	13.3	12.8	12.8	0.5	0.5	0.0
	0.5–1	16.0	14.9	15.2	0.8	1.1	−0.3
	1–2	15.2	15.1	13.4	1.8	0.1	1.7
June 25	0.0–0.5	9.0	12.7	7.5	1.5	−3.7	5.2
	0.5–1	16.0	16.2	13.0	3.0	−0.2	3.2
	1–2	14.8	15.4	14.6	0.2	−0.6	0.8
	2–3	12.7	12.6	12.1	0.6	0.1	0.5
July 2	0.0–0.5	5.0	5.8	1.3	3.7	−0.8	4.5
	0.5–1	14.1	11.4	6.6	7.5	2.7	4.8
	1–2	13.9	12.7	12.4	1.5	1.2	0.3
	2–3	12.6	11.3	12.3	0.3	1.3	−1.0
July 9	0.0–0.5	9.0	8.5	5.7	3.3	0.5	2.8
	0.5–1	10.5	9.9	6.6	3.9	0.6	3.3
	1–2	14.4	13.4	11.7	2.7	1.0	1.7
	2–3	12.4	11.9	12.4	0.0	0.5	−0.5
	3–4	12.8	9.4	8.6	4.2	3.4	0.8
July 19	0.0–0.5	8.6	5.1	0.8	7.8	3.5	4.3
	0.5–1	12.6	6.9	3.8	8.8	5.7	3.1
	1–2	12.8	10.6	6.3	6.5	2.2	4.3
	2–3	11.6	11.1	8.7	2.9	0.5	2.4
	3–4	11.4	8.1	5.5	5.9	3.3	2.6
July 28	0.0–0.5	9.7	7.7	7.4	2.3	2.0	0.3
	0.5–1	12.8	6.6	5.0	7.8	6.2	1.6
	1–2	12.9	8.9	6.6	6.3	4.0	2.3
	2–3	11.3	10.8	5.4	5.9	0.5	5.4
	3–4	11.6	8.0	7.2	4.4	3.6	0.8
Aug. 5	0.0–0.5	8.6	5.2	3.0	5.6	3.4	2.2
	0.5–1	12.0	5.0	4.2	7.8	7.0	0.8
	1–2	12.7	8.6	6.6	6.1	4.1	2.0
	2–3	11.1	9.4	8.4	2.7	1.7	1.0
	3–4	11.2	7.4	7.1	4.1	3.8	0.3

A survey of the available nitrates (Table 17) shows that the uncropped area (with one exception) had the largest supply, differences being found to a depth of 24 inches toward midsummer when the root systems were well developed. The nitrate supply was, with one exception, less in the surface scraped than in the deeply hoed plats. Thus the deeply cultivated plat was not only more moist but richer in nitric nitrogen. It has been shown that nitrate production in soils at Lincoln is insignificant at a moisture content as low as the hygroscopic coefficient[130] but increases with an increase in the moisture content. In some cases it reaches a maximum at a relative soil saturation of 60 per cent.[47]

TABLE 17.—NITRIC NITROGEN IN PARTS PER MILLION IN THE SEVERAL PLATS, 1926

Date	Depth, inches	Uncropped soil	Cropped deeply hoed soil	Cropped, surface-scraped soil
June 2	0– 6	33.5		14.9
June 9	0– 6	31.0	21.6	19.4
June 19	0– 6	38.5		30.4
	6–12	21.2		9.8
July 3	0– 4	34.6	31.6	30.1
	4–12	18.9	19.7	12.1
	12–24	6.8		3.8
July 10	0– 4	39.5	29.3	32.2
	4–12	21.4	11.8	
	12–24	6.8	4.4	
July 19	0– 6	47.0		24.1
	6–12	16.1		6.1
	12–24	7.1		3.1

No differences could be seen in the development of the plants in the two plats. Because of the dry season and a severe case of blossom-end rot yields were not determined.

Similar experiments with tomatoes at Ithaca, N. Y., showed that the crop responded to cultivation which was more than simply to kill the weeds. Yields, however, were only slightly in favor of the cultivated over the scraped plat.[152,158] A six-year average, however, showed no significant increase in yield due to cultivation as compared with scraping to keep down weeds. Here, as in so many phases of vegetable production, more experimental evidence under different climatic conditions is needed.

Experiments made in Indiana showed a marked increase in yield as a result of thorough cultivation when compared with usual cultivation. In the plats not thoroughly cultivated "weeds sprang up during the latter part of the season and considerable amounts of moisture were lost on account of lack of a dust mulch."[14] The plants did not present as thrifty an appearance and did not grow so rapidly as those receiving thorough cultivation. The increase in yields were 2.11, 4.03, and 3.87 tons per acre, respectively, for the 3 years during which the experiment was under way. After the vines thoroughly covered the ground only shallow hoeing was found best. Similar results have been obtained in New Jersey.[5]

Root Habits in Relation to Cultural Practice.—The extensive and vigorous root system and its thorough occupancy of a large volume of soil helps to explain why tomatoes are successfully grown on all types of well-drained soil. It is indeed among the least exacting of the vegetable crops. In considering the relation of roots to soil, attention should be directed to the nutrient, water, and air relations of the substratum. Plants are directly dependent on these for growth rather than on any certain proportions of silt, clay, and sand. A soil with a good supply of humus, thus affording a fairly open structure, moderately rich in nutrients and one that is well drained and warms readily and yet retains sufficient water to insure a constant supply during drought, would seem ideal for the best root development. For quick growth and rapid maturity a lighter soil is preferable and perhaps a heavier one for the late-maturing crop.

Preparation of the Soil.—Preparing the soil is making an environment more favorable for root growth. When tomatoes are transplanted, the field should be in the best of tilth for the reception of plants. Thorough soil preparation is especially connected with the reestablishment of the root system of the transplanted plants. No amount of concentrated nutrients will compensate for a soil in poor physical condition from lack of humus and proper cultivation. Getting the soil in excellent condition before transplanting greatly insures the prompt reestablishment of the seedlings and less disturbance of the root system during later cultivation. A good supply of water is necessary at all periods of development. Well-tilled soils are more retentive of water than those in poor physical condition. Deeper plowing than usual aids in securing a more deeply pene-

trating root system Plants with deeply penetrating roots are most assured of an even moisture supply, under irrigation they do not require so frequent watering, neither do they suffer from the sharp fluctuations of alternately having too much or too little water It has been suggested that many of the troubles affecting tomato plants in California, and this probably applies elsewhere, are connected with shallow root systems [121]

Transplanting —Since the tomato plant is tender and cannot be grown in the field until danger of frost is passed, the crop is grown from plants started in greenhouses, hotbeds, or cold frames The greatest yields and profits are obtained from well-grown, early set plants [70 5] The relation of the root system to transplanting is an important one

Usually the seedlings are transplanted when they are about 2 inches high and more space given each In this process the roots are more or less severely pruned and the new root system is much more fibrous Frequently a second transplanting is made in which each plant is given still more room or transplanted in a suitable receptacle such as a flowerpot, paper band, tin can, etc

Since the root system is disturbed and the development of the plant more or less checked at each transplanting, it might be concluded that plants grown from seed sown directly in pots or other containers would grow more vigorously and give a higher yield than those once or twice transplanted In fact this has been shown by numerous investigations to be the case That transplanting in itself does not promote an early crop nor an increased yield has been also clearly demonstrated In an experiment in Wisconsin

> three crops of tomatoes were grown In each case seeds were planted singly in 6-inch pots in the greenhouse, when the plants were about 2 inches in height, two-thirds of the whole number were dug up and reset in the same pots, later, one-half of these were again transplanted in a similar manner As soon as weather permitted, 10 plants of each lot were knocked from the pots and set 4 by 8 feet apart in open ground, every precaution being taken to avoid injury to the roots [29]

Those not transplanted yielded more than those once transplanted, while those twice transplanted yielded least The total for 10 plants with each treatment during a 3-year period was, 1,175, 1,131, and 1,001 pounds, respectively

That early production is influenced by reducing root injury in transplanting is shown by the following experiment. Seeds of the Bonney Best variety were sown in the greenhouse. Seven days later some seedlings were transplanted 3 by 4 inches in a greenhouse bench. Others were set 2 by 2 inches in flats. Approximately a month later the flats were thinned by removing alternate plants. The plants thus removed were set in 4-inch pots. Another lot of seed was sown a week after the first transplanting. These seedlings were not transplanted. All four lots were set into the field on May 12, 4 by 4 feet apart. The potted plants, which were no larger than the plants in the flats but had a better root system, grew much faster than the others. They came into bearing early in the season when the price was high and gave by far the greatest financial returns, although the plants from the greenhouse bench and flats gave practically the same total yields.[70]

> Some of the most successful northern growers complete the indoor growth of the plants in 6-inch clay pots such as are used by florists. By keeping the plants cool and well ventilated toward the last of their indoor period they become very strong and stocky, having a wonderful root system.[8]

The advantages of transferring plants into the field with an undisturbed root system have been repeatedly and very clearly shown.[13]

Fortunately the tomato is a plant that well withstands transplanting compared to many vegetable crops (p. 119). Suberization and resulting loss of absorption by the older roots slowly take place, there is a very high degree of root branching, and the proportion of actual root area to tops is very large. This accounts for the fact that plants even 10 to 12 weeks old that have been provided with sufficient room to make a steady growth may be profitably transplanted providing the root system is not seriously disturbed. For a week or 10 days before transplanting to the field, the plants should be hardened. This is accomplished by leaving the hotbeds open and adding only enough water to keep the plants from wilting very badly.

> Under these conditions [of wilting] the fine, tender rootlets, and root hairs are largely destroyed, but the plant promptly throws out a vigorous cluster of new ones. In fact, the new set of roots possesses greater vigor

than those on a seedling that has not been allowed to wilt, in the latter case the roots are not injured beyond recovery, and it appears that their recovery prevents the prompt development of new ones [118]

In transplanting it is the practice to lift the plants with most or all of the roots and to leave as much soil as possible on the roots When the plants have been grown in the cold frame, blocking is practiced to get as much of the root system and soil as possible The blocking is usually done about 10 days before the plants are lifted This early blocking cuts the long roots and promotes the development of lateral roots which ramify the soil block and hold the soil more tenaciously This facilitates handling and lessens checking of growth due to the operation of transplanting [70] Unless a moist ball of earth clings to the roots, a condition promoted by watering a few hours before transplanting, they are sometimes dipped into a paste made of clay and water This keeps the roots from drying out and also brings them in close contact with the soil after transplanting They are thus better able to withstand the check of transplanting into the field The practice of transplanting on a cloudy day or late in the afternoon is a good one since at such times transpiration is less and sufficient water may be absorbed even by a more or less disturbed root system to supply the needs of the plant Transplanting into a moist soil or watering the plant after transplanting promotes the same end The soil, however, should not be too wet or puddled since this destroys its tilth and retards root aeration Dry soil placed about the freshly watered plant prevents the surface from drying and forming a crust

Setting the plants several inches deeper in the soil than they were in the seed bed or container is beneficial since the plant will stand up better and the new roots will develop along the stem The taller the plants the deeper they should be set This promotes the growth of a larger and more deeply penetrating root system than where the plants are shallowly set Experiments in which the plants were set only as deeply as they had been growing in pots resulted in later fruit production, a smaller total yield, and fewer and smaller fruits Deep planting also holds the plant erect and rigid and reduces injury from strong winds shortly after transplanting and before the roots are reestablished

Spacing —Spacing of tomatoes varies with the variety, soil, season in which the crop is grown, etc , but is entirely empirical and without reference to root extent That spacing should be

more distant on rich soils is not in agreement with the fact that in a well-fertilized substratum and especially in one rich in nitrogen a root system is often more concentrated Because of the greater development of tops under such conditions, however, spacing is usually more distant A study of the root development of different varieties on various soils should yield interesting and practical results

Cultivation —In the process of transplanting, the soil becomes compacted about the plants, a condition promoting water loss and retarding aeration Hence, the practice of cultivation soon after transplanting is an excellent one It is usually deep enough to mellow the soil about the plant roots and thus promote their rapid elongation Ridging soil about the stems makes them more resistant to the wind and promotes a copious development of adventitious roots The importance of thorough cultivation to keep out competing weeds and conserve moisture for the roots has been fully demonstrated The straw mulch, which is sometimes used, is very effective in conserving moisture, especially for the latter part of the season when plants often suffer from drought It undoubtedly permits the roots to grow and function in the soil surface and is a very efficient means of controlling blossom-end rot, a physiological disease resulting from drought Mulching may have a harmful effect, however, in retarding or modifying bacterial activity and hence in decreasing the supply of nitrates available to the roots for absorption [1]

Fertilizers —Fertilizing the soil should be done with a thorough understanding of its relation to root development The common practices of drilling and mixing the fertilizer in the row or applying it broadcast and mixing it thoroughly with the soil before the plants are set seem excellent To make a good growth before the root system is widely spread, the plants need a good supply of readily available fertilizer Experiments have shown that where the fertilizer is applied and well mixed in the row that the production of early fruit is greatly increased [116] In spring and early summer the root activity is greatest in the shallow soil layer which is usually moist and hence the fertilizer is available Later the surface soil may become so dry that the roots can secure neither water nor nutrients from it except when irrigation is practiced Thus fertilizers applied later in the season might be quite ineffective One of the advantages of setting the plants into the field early is the greater possible use of fertilizers Few plants respond

more quickly or more profitably to a proper use of fertilizers than the tomato

Pruning —Pruning the vines, *i e* , pinching out all or nearly all of the lateral branches as soon as they appear and thus confining the growth to one or a few stems and training these remaining stems is a practice used by some growers especially in the South [140] It has been suggested that any benefit thus derived may be due to a lessening of foliage diseases, which are more severe in the South, since trained plants are thus benefitted by better exposure to wind and sun [157] In the North it has been largely discontinued since it has been found unprofitable In general the yield decreases in proportion to the severity of pruning [176 120] For example, at Urbana, Ill , plants pruned to a single stem gave a yield of 6 5 pounds of marketable fruit, those pruned to 2 stems yielded 10 5 pounds, those with three stems 12 1 pounds, but plants not pruned gave a yield of 19 6 pounds [90] Indeed, hundreds of pruning experiments have been done without reference to the effect upon the root system There is a close correlation between root and shoot development and the maintenance of a proper balance between them is of very great importance If either is too limited or too great in extent, the other will not thrive Unpublished studies at Cornell University show that the root system of a pruned tomato plant is reduced in about the same proportion as the top "Hence it seems probable that pruned plants suffer more from drought than unpruned plants because the former cannot get as much of the available moisture as the latter "[157] This is further indicated by the fact that blossom-end rot is nearly always more severe on trained and pruned than on unpruned plants

Pruning the roots by pulling on the plants and thus breaking the root system to a considerable extent stimulates early ripening of the fruit Of course such treatment early in the season is harmful In North Dakota two varieties of tomatoes thus pruned early (July 23 and Aug 17) produced a smaller total crop than those unpruned Late pruning (Sept 1), however, resulted in a decided increase in total yield Plants thus stimulated practically ripened all of their fruits before the end of the season [175]

Effects of Roots on Soil —The roots of tomatoes leave the soil in a good mechanical condition The roots and stubble contain more fertilizing elements than those of most other crops For example experiments in Delaware have shown that the weight

of roots and stubble is practically 9,000 pounds per acre This is 4 4 times that of cowpeas, 3 times that of wheat, and 3 5 times that of the white potato The roots and tops of the tomato contained per acre 27 3 pounds of nitrogen, 4 1 pounds of phosphoric acid, and 33 9 pounds of potash [99]

Vegetable growers report various instances of reduced yields of some crops following certain plants It is the belief among muck soil truckers that carrots have a depressing effect on onions, celery, and lettuce Cabbage is reported to depress the yield of corn, that is, the yield is lower following cabbage than when corn follows corn [153]

It has been clearly demonstrated that the presence of sorghum roots and stubble has a distinctly depressing effect upon the yield of wheat [136] Preliminary field and pot tests with tobacco indicate that the injurious effects of preceding crop plants come mostly from the roots rather than the tops of these plants Roots of potatoes, hairy vetch, and corn retarded the growth of tobacco even when their aboveground parts were removed from the field in harvesting [41]

Experiments in Rhode Island have shown that.

The divergent effect of crops on those which follow seems not to be attributable, at least principally, to differences in the amount of nutrients removed by the crops grown previously, that is, the smallest yield may not occur after the crop which removed the largest amount of even the most-needed nutrient

The soil acidity was affected differently by the several crops and, generally, the best yields of the onion, a plant which is sensitive to conditions accompanying acidity, followed the crops giving rise to the least acidity These indications assume added importance because of the observed fact that the effects of the crops on those which follow were much less divergent if the soil acidity was reduced by liming

Even if later work should prove that preceding crop effects are not important in connection with a neutralized soil, attention should nevertheless be given by the practical farmer to the very potent influences which have been observed in the present work, for the reason that so many soils have a greater degree of acidity than existed in these experiments, and it is doubtful if they will ever be limed sufficiently to maintain them in a neutral condition [51]

CHAPTER XXVII

EGGPLANT

The eggplant (*Solanum melongena esculentum*) is a rather coarse, erect, annual, branching herb It reaches a height of 2 to 4 feet and becomes somewhat woody Like its relative, the tomato, it is grown for its fruit Eggplant requires a high temperature for its best growth, and consequently it is cultivated commercially mainly in the South It is rather a common crop in the home garden throughout much of the United States, however Like tomatoes, eggplants are usually transplanted into the garden but this must be done in such a manner that the root system is not disturbed to an extent which will check the growth of the plant Hence, they are transplanted at least once, often into pots, boxes, or bands, from which the whole soil-root mass may be set into the field with a minimum of injury to the roots

In the following studies plants were grown from seed sown in the field on June 2 Seed of the Black Beauty variety was used The plants were spaced 2 5 feet apart in rows 3 feet distant

Early Development—Owing to dry weather the plants grew slowly and on July 24 they were only 6 inches tall Each plant had six or seven leaves in addition to the cotyledons which were still green The leaf blades were about 3 5 by 2 inches in greatest dimensions although the largest were 5 by 4 inches and thus presented considerable surface

The underground parts were characterized by a strong taproot which, with its deeper branches, furnished the major absorbing area In addition, a large number of more superficial, horizontally spreading roots ramified the surface soil A lateral spread of 18 inches and a maximum depth of 34 inches had been attained (Fig 77)

The surface inch of taproot, which was 7 millimeters thick, was free from branches but the next inch had 30 simple rootlets 0 5 millimeter thick and about 0 3 inch long Twenty were found on the third inch of taproot Like the others, they often occurred in clusters or clumps Among these were a few longer,

rebranched roots Below this to a depth of 2 feet branches originated at the usual rate of 5 to 9 per inch Those in the surface 6 inches ran horizontally for distances of 3 to 18 inches They were branched at the rate of 5 to 8 laterals per inch, the branches being irregularly grouped and varying from 0 3 to 2 inches in length A few were longer (8 to 11 inches) and usually pentreated more or less vertically downward These were quite

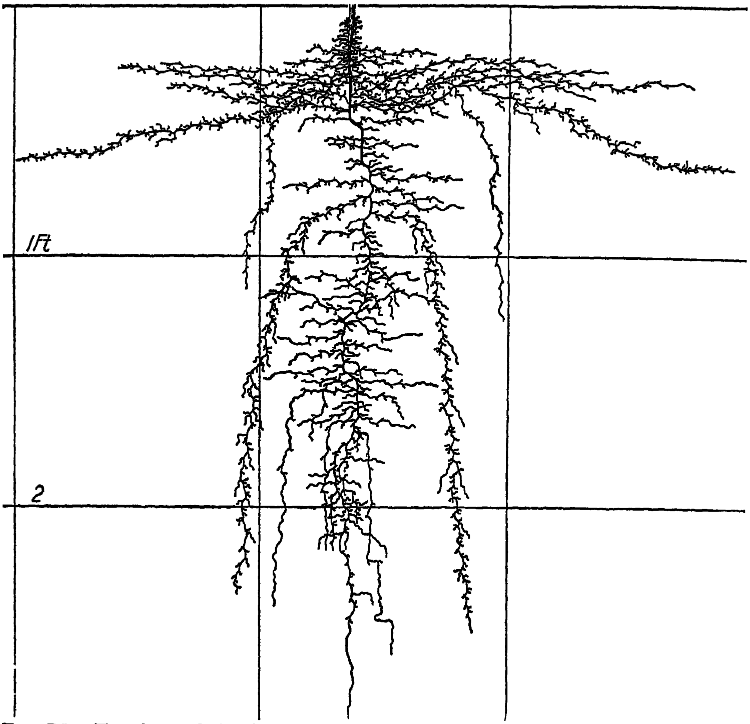


FIG 77 —Eggplant of the Black Beauty variety showing the root extent at the age of about 7 weeks

well rebranched In the next 3 inches the branches were shorter but at still greater depths numerous long ones occurred Their course was horizontal or obliquely downward for a short distance, usually 1 to 3 inches, and then more vertically downward As a whole only the longer, deeper roots were as well branched as those in the shallower soil In fact many of the deeper, rather horizontal, shorter laterals were poorly furnished with branchlets The very sinuous course of the taproot and of many of the

smaller roots was marked Considering the size of tops the root system was well developed

Mature Plants—A second and final examination was made Oct 3 As a result of favorable moisture conditions late in the summer the plants had made a good growth They averaged 33 inches in height and the tops had a spread of 20 inches Plants of average size were used for root studies Each plant had 5 to 7 branches and 75 leaves The leaf blades averaged 8 inches in length and 5 inches in width, thus exposing a very large transpiring surface The plants were fruiting abundantly The fruits ranged from only 1 inch to 5 inches in diameter The small size was due to the retarded growth during the dry weather of early summer

The root system had made a most marked development The strong taproot was approximately 1 inch in diameter near the soil surface It tapered to 4 millimeters in thickness at the 12-inch level but like many of its large laterals was 2 millimeters in diameter throughout much of its tortuous course Due to density of roots and the great water loss by the tops, the soil in this plat was quite dry and hard This condition was reflected in the crooked course pursued by most of the roots, short zigzags and kinks through distances of only an inch or two being characteristic

That the surface 12 inches of soil was overcrowded with roots should be clear when it is stated that a single plant had 275 smaller main roots in this soil area as well as 18 larger ones Most of these roots, which were only 1 millimeter or less in diameter, extended 8 to 14 inches horizontally from the plant and ended or turned downward for a few inches No roots were found at greater distances than 2 feet All were branched very profusely to the second and third order and formed dense root masses Some were yellowish brown and showed decay

Of the 18 larger roots originating in the surface 15 inches of soil (and all but 2 in the surface 10 inches) nearly all ran horizontally, or only slightly obliquely downward, for distances seldom exceeding 2 feet Then, turning downward, they ran vertically or again obliquely to depths of 4 to 7 feet

A fair idea of the general behavior of the main roots may be gained from the following example One lateral 5 millimeters in diameter originated at a depth of 3 5 inches It ran almost horizontally so that when 16 inches long it was only 7 inches deep Then it turned abruptly downward after giving rise to 4 rather

horizontal branches. These extended outward and upward 19 to 24 inches further and ended within 2 to 4 inches of the soil surface. The large main root continued its downward course but gave rise to no large branches until it reached the 18-inch soil level. Here 7 rather equal branches about 1 millimeter in diameter arose. The main root continued its vertically downward course to an ultimate depth of 6.8 feet. The branches spread 2 to 18 inches on all sides and then turned downward. This system of 8 roots and their network of branches completely ramified the fourth, fifth, and sixth foot of soil at least for a distance of 8 inches or more on all sides of the main root. Horizontal and vertical branches were very profuse in the joints of the clay, filling it with a white, glistening network. The smallest branches were hairlike.

It is difficult to visualize this intricate network of roots in the deeper soil. It should be pointed out, however, that many of the roots reached depths of 5.5 to 7 feet, that numerous long branches greatly increased the absorbing territory, and that both main and subsidiary roots were clothed with laterals 0.5 to 5 inches long at the rate of five to eight per inch, the longer ones being rebranched.

The mass of absorbing roots in the surface soil can scarcely be overdrawn. In contrast the well-ramified deeper soil seemed rather poorly occupied. The small branches from the horizontal portions of these major laterals were often 8 to 12 inches long. As many as 14 frequently arose from a single inch of root length. They were extremely well rebranched, forming a dense root network to the very soil surface and indeed throughout the 12 inches of the richest surface soil. The ultimate branchlets averaged 7 per inch and were 0.2 to 1 inch long.

The taproot frequently divided at depths of 15 to 18 inches where the hardest soil occurred. Even near its end, or the end of one of its forks, it sometimes divided into a whole cluster of fine rootlets. Although somewhat poorly branched throughout, on certain portions of its course small branches occurred nearly to the tip.

The total absorbing surface of such a root system must be very large indeed. Just how much of it is actively functioning late in the life of the plant, *i.e.*, during flower and fruit production, is a problem of considerable difficulty but of great physiological importance.

Summary —Eggplants grown from seed are only 6 inches high when 7 weeks old The strong taproot has penetrated nearly to the 3-foot level Numerous horizontal branches spread 12 to 18 inches in the surface 3 to 8 inches of soil Other branches, some 2 feet long and running obliquely downward, arise from the deeper portions of the taproot, spread 6 to 8 inches on all sides of it, and furnish the larger absorbing area On mature plants the root system is very extensive Nearly 300 roots often arise in the surface foot of soil Most of these merely ramify the soil 8 to 14 inches from the plant But 15 or more stronger laterals usually run outward 1 to 2 feet and then penetrate downward 4 to 7 feet Their long, horizontal branches extend the lateral spread to 4 feet Even in the deeper soil a lateral spread of 3 5 feet is common The absorbing system in the surface soil is quite as profuse as that of the tomato and can be scarcely overdrawn The deeper portion of the taproot is rather poorly branched But the deeply descending laterals are so well branched and so well furnished with delicate rootlets that it presents an enormous absorbing surface In contrast to the tomato, the root system of the eggplant is not so widely spreading but penetrates much deeper

Other Investigations on Eggplant —Investigations in Germany have shown that the general root habit of eggplant is very similar to that of the tomato No essential differences were observed either as to lateral spread or branching The greater mass of the roots attained a depth of about 33 inches [89]

The roots of the eggplant of the Black Pekin variety were washed from the soil at Geneva, N Y , late in September

> The main roots radiated from the base of the stem at varying angles but the majority rather inclined to the perpendicular The horizontal roots were smaller in size than those that grew downward and none reached a greater length than 2 feet Branches were most numerous near the base of the stem [41]

The main roots were 4 to 6 millimeters in diameter

Many of the cultural practices discussed under tomato also apply to the eggplant

CHAPTER XXVIII

PEPPER

Pepper plants (*Capsicum frutescens grossum*), although biennials or perennials in warm climates, are cultivated as annuals in the United States The plant is not unlike its relatives, the eggplant and tomato, in regard to its size and cultural requirements and like them also is grown for its fruit Being a warm climate plant it requires a long growing season and consequently is usually started in hotbeds or greenhouses and transplanted into the field

Plants of the Large Bell or Bull Nose variety were transplanted into the experimental field at Norman, Okla , May 2 They were grown in rows 3 5 feet apart, the plants being placed 2 feet distant in the row They soon became established and grew vigorously.

Early Development.—On May 26 the first root examination was made The taproots had been injured in transplanting and the result was a strong development of laterals In each plant from 54 to 76 branches of variable length had grown from the original taproot and base of the stem These originated in rows on opposite sides of the plant The larger ones were 1 millimeter in diameter Most of the roots spread rather horizontally, some obliquely, and a few penetrated quite vertically downward A lateral spread of 15 inches and a maximum depth of 17 inches were found (Fig 78) On the larger roots, near the base of the plant, laterals with a maximum length of 2 5 inches occurred at the rate of four to six per inch Farther out they were fewer and shorter, and the last 2 to 3 inches of root ends were unbranched

Half-grown Plants—At the second examination, 2 weeks later (June 10), the plants were 8 inches high and the diameter of the tops was almost 1 foot Flower buds were appearing The root system consisted of 40 to 60 strong laterals about 1 millimeter in diameter and 20 to 30 smaller ones All originated in the surface soil at depths of 2 to 6 inches from the main axis of the plant,

which was about 5 millimeters in diameter. Branches arose from two sides of the old taproot. The general shape of the root system had not changed although its area for absorption had been greatly increased. Figure 79 shows the great network of absorbing roots. The horizontal roots rather completely filled the surface foot of soil to 18 inches on all sides of the plant, a few turning downward near their extremities. The obliquely and vertically penetrating roots occupied the third 6-inch level. The

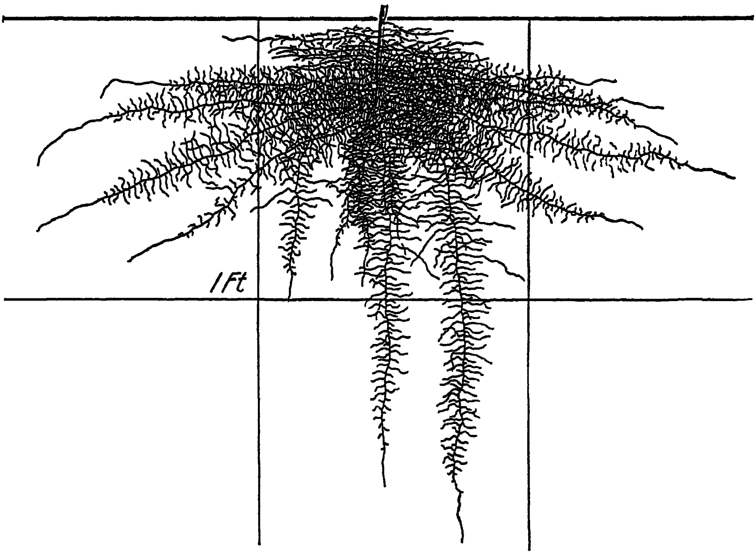


FIG. 78.—The root system of a Large Bell pepper plant 24 days after transplanting into the field.

maximum depth was 2 feet. The finer branches formed a great network in the moist, sandy soil.

Maturing Plants.—A final examination was made July 17. The plants were 20 inches high and for some time had been bearing fruit. The stalks were nearly 1 inch thick but the bushy tops did not cover the ground between the rows. Root development had kept pace with that of the tops. The strong laterals were 3 to 5 millimeters in diameter. Those that ran horizontally usually turned downward, 1 to 2 feet from their origin, and extended into the second or third foot of soil. The vertically and obliquely penetrating roots were usually deeper, a few reaching the 4-foot level. The older portions of these roots, *i.e.*, the first 1 to

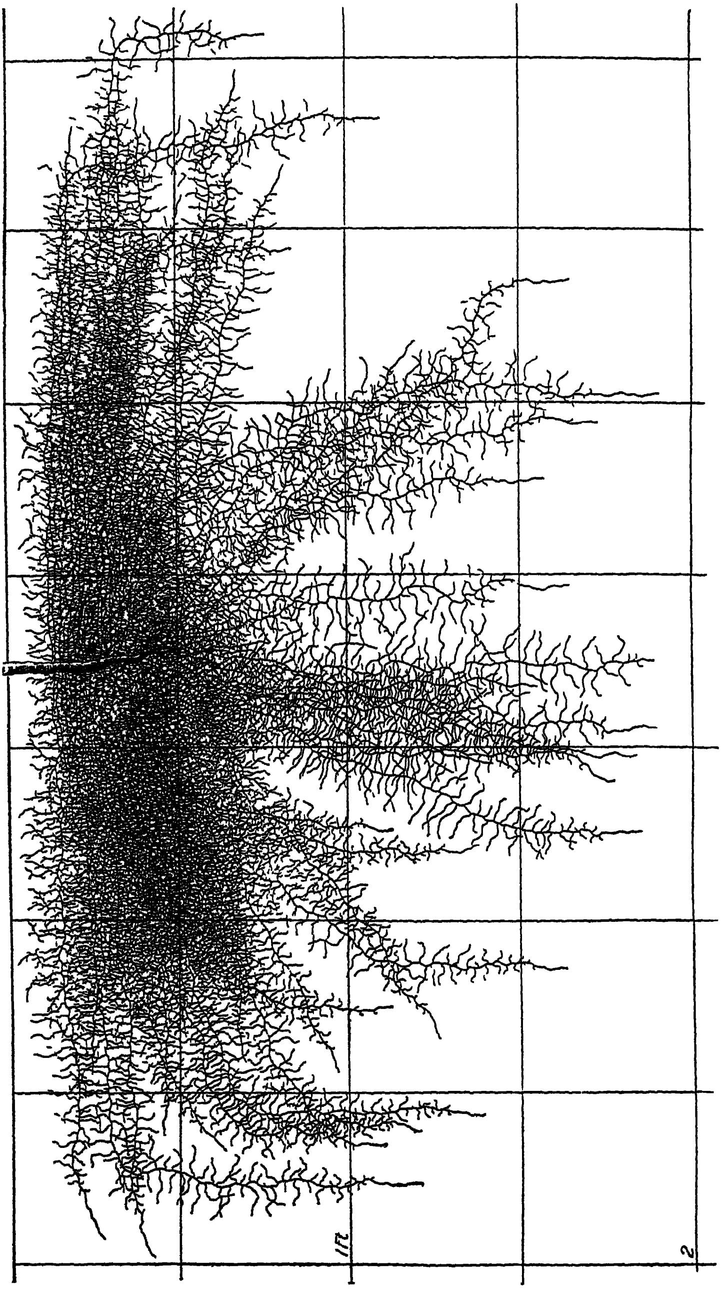


Fig 79 —Root system of a half-grown pepper about 6 weeks old

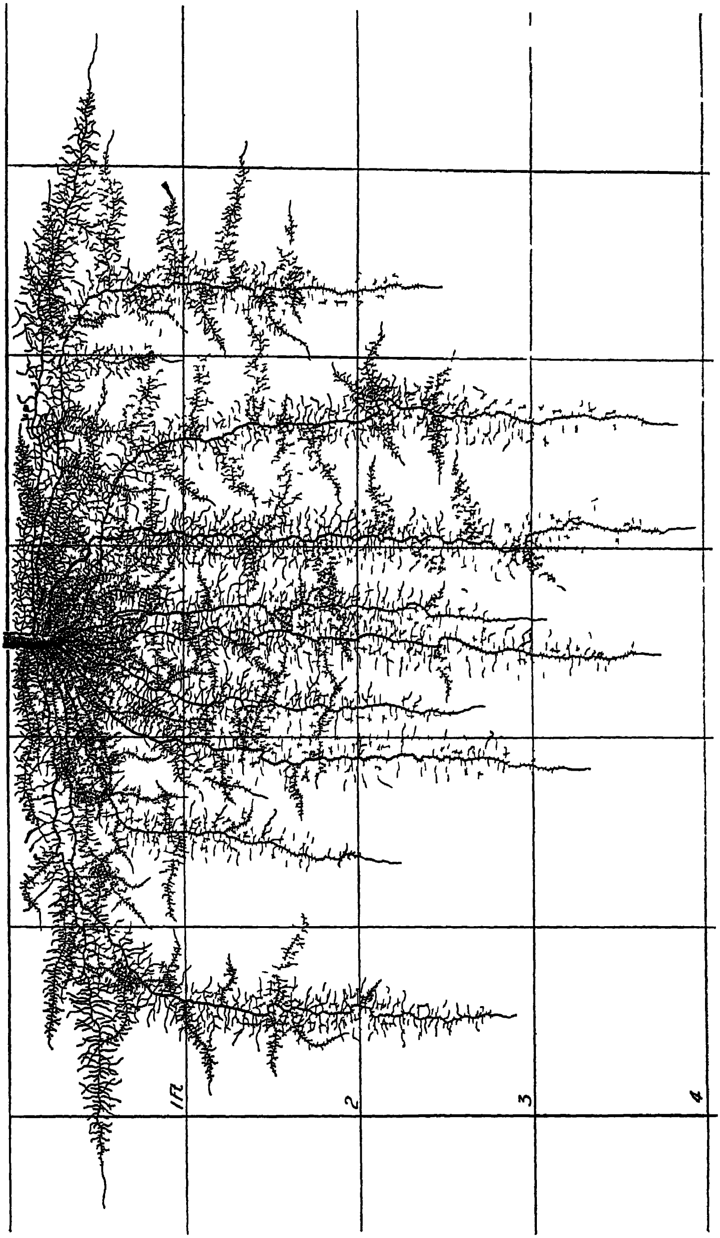


FIG. 80 — About one fourth of the root system of a nearly mature pepper

1.5 feet, were poorly clothed with laterals and probably carried on little absorption. But their distal portions were densely covered with branches, the longer of these being profusely rebranched (Fig. 80).

Absorption just beneath the plant and in the soil longest occupied was afforded by a network of shorter, finer, but well-branched roots arising from the old root-stem axis. A total of 90 roots was found on a large plant. These, with their multitude of branches, filled the soil to 2.5 feet on all sides of the plant from the very surface to a depth of 3 to 4 feet.

Summary.—Pepper has a strong taproot which is usually injured in transplanting. From the remainder of the taproot and the base of the stem very numerous, profusely branched laterals arise. These grow from horizontally outward to vertically downward, the bulk of absorption during the early life of the plant occurring in the surface foot of soil. When the flower buds appear, the root system thoroughly fills the soil 1.5 feet on all sides of the plant to a depth of 1 foot. Beneath the plant the second foot of soil is also quite thoroughly occupied. Mature plants have a lateral spread of 3 feet, the formerly horizontal laterals often turning downward into the second or third foot of soil. More oblique or vertical roots reach depths of 3 to 4 feet. With the finer branches, these form a very intricate and efficient absorbing system.

Root Habits in Relation to Cultural Practice.—Much of what has been said about the preparation of soil, transplanting, and cultivation of the tomato applies also to the pepper. Where the seed is sown in hills in the field great care should be exercised in thinning, especially if the seedlings are thick, so as to disturb as little as possible the roots of the plants left. When possible, irrigation is advised after thinning to prevent wilting.[36] In the North, well-grown, potted plants, because of the earlier formation of fruits, have a much better chance of producing satisfactory yields before the close of the growing season than plants that are small or poorly developed at the time they are set into the field.[94] Like the tomato, the pepper has a widely and deeply spreading root system but one also which thoroughly occupies the surface layer of soil. Hence only shallow tillage should be employed, after the plants have made any considerable growth, although deep tillage soon after the plants are set into the field loosens the soil and promotes vigorous root development. The usual spac-

ing of plants, about 18 inches apart in rows 2 to 3 feet distant, is not so great but that all of the soil is thoroughly occupied by the roots Indeed there is much competition between adjacent plants for water and nutrients Although the plants will stand considerable drought, under the rainfall of Illinois, irrigation increases the yield [94]

CHAPTER XXIX

CUCUMBER

The cucumber (*Cucumis sativus*) is a common and important vine crop. It is grown largely for its unripe fruits which are used for pickles and to slice for salads. Cucumbers are raised not only in market gardens and on truck farms but also very commonly in the home garden. It has so much in common with other cultivated members of its family, the *Cucurbitaceae*, that a general statement may be helpful before treating each in detail.

The Cucurbits or Vine Crops.—All of the chief economic species of the group of cucurbits, *viz.*, the cucumber, the muskmelon, the watermelon, the citron, the squash, and the pumpkin are tender, tendril-bearing, annual vines, which thrive only in hot weather. In aboveground development and in similarity of root habit they resemble each other very much. Hence, it is not surprising that they are also very similar in cultural requirements. They are long-season crops, transplanted with difficulty when the roots are disturbed, and nearly always grown in widely spaced hills.

In the development of the seedling the thick, food-stored cotyledons are pulled out of the ground by the arched hypocotyl. This necessitates care in preventing the formation of a soil crust which would make emergence difficult and also decrease aeration to the vigorously developing roots. A taproot, several inches in length and much branched, is usually formed before the plumule unfolds. This emphasizes the importance to the plant of extensive contact with the water of the soil, food being available for a considerable period from the rather thick cotyledons. The root development, at least of one variety of each of the important species, has been thoroughly studied.

Early Development of Cucumber.—Cucumbers of the White Spine variety, one that is best known and most widely grown, were planted June 16. The hills were spaced 5 feet apart. When the plants were well established, they were thinned to 2 or 3 per hill.

On July 13, when the first examination was made, the plants averaged 5 inches in height and the total spread was 8 inches. Plants of average development had about 17 leaves, usually 7 of which were fully grown. Since the larger leaf blades had a length and diameter of about 4.5 and 3.5 inches, respectively, the transpiring area already was considerable.

The cucumber has a rather thick taproot about 6 millimeters in diameter near the soil surface but tapering to 1 millimeter or slightly less below 12 inches. It branches widely in the surface 6-inch soil layer, penetrates quite vertically downward, usually

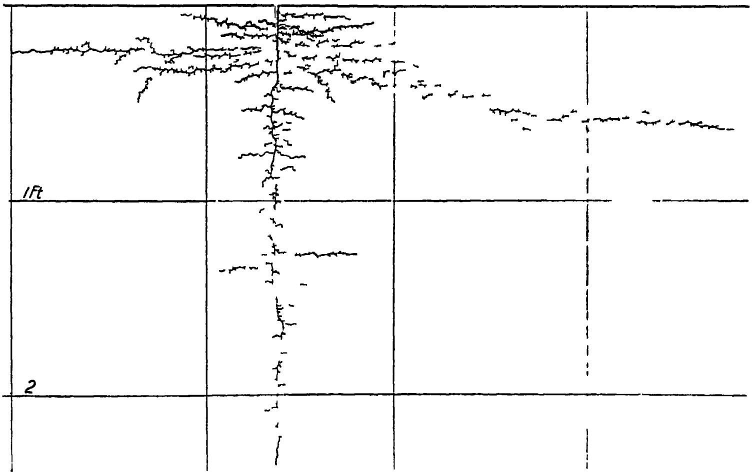


FIG. 81.—White Spine cucumber root system about 4 weeks old.

with long gentle curves, and reaches depths of 25 to 28 inches. On a typical plant the first 5 inches of taproot gave rise to 11 laterals, 0.5 to 1 millimeter thick, and six smaller ones. These began to appear abundantly about 1 inch below the soil surface. They pursued a generally horizontal although somewhat sinuous course, rarely ending more than 2 to 3 inches above or below their point of origin. The longer ones extended laterally for distances of 18 to 24 inches. One large lateral, which branched at the rate of three to six rootlets per inch, had a maximum spread of 29 inches. Its branches, as was characteristic for other similar roots, varied from 0.1 to 2 inches in length and the longer ones were rather well furnished with short branches (Fig. 81).

Aside from the longer main laterals, numerous shorter ones were found. In fact below 6 inches most of the rootlets did not

exceed 1 5 inches in length, many were shorter, a few were 6 inches long All of the roots were more or less horizontal in direction of growth, although quite curved The shorter ones were entirely unbranched Frequently the older portions of the laterals were of smaller diameters than the rapidly growing distal portions The younger roots were delicate and thread-like, the older and larger ones rather tough Both those of the deeply penetrating taproot and the widely spreading, surface-absorbing system were white in color The rather meager root development during the middle of July, compared to the extensive roots of many vegetable crops at this time, should be noted Later the plant makes a remarkably rapid growth

Half-grown Plants —Two weeks later, July 27, the plants had begun to blossom The vines were 8 to 13 inches long The leaves, which were about 4 inches long and only slightly less in diameter, occurred at the rate of 18 to 25 per plant

The taproots were 0 3 inch in diameter and even in the deeper soil maintained a diameter of 1 millimeter or more Evidently stimulated by moist soil resulting from recent rains, they had given rise to as many as 55 small roots in the surface 1 or 2 inches of soil These, however, did not exceed 1 inch in length and were only poorly or not at all rebranched The general root habit differed but little from that of the previous examination, the widely spreading surface laterals and the vertically penetrating taproot being the important features The taproots now reached depths of 36 to 44 inches Below 10 inches the branches on the taproots were short Many of them extended outward only 1 to 2 inches, although a few were 4 inches or even more in length, and with their sublaterals formed a small network A rate of four rootlets per inch was usual The occurrence of roots in pairs or small groups was frequently noticed As the taproot elongated, it became clothed with short branches, except the last 6 to 8 inches which were quite smooth

The horizontally spreading roots in the surface soil had made a marked growth They had also increased greatly in number (Fig 82) Usually a taproot had at least 8 large branches arising in the surface 10 inches of soil and intermixed with these 8 to 14 shorter ones per inch The larger laterals were often 2 millimeters thick and, like the smaller ones, ran quite parallel to the soil surface often to distances of over 3 feet The longest ended 50 to 55 inches from the taproot and at depths of only 3 to 9

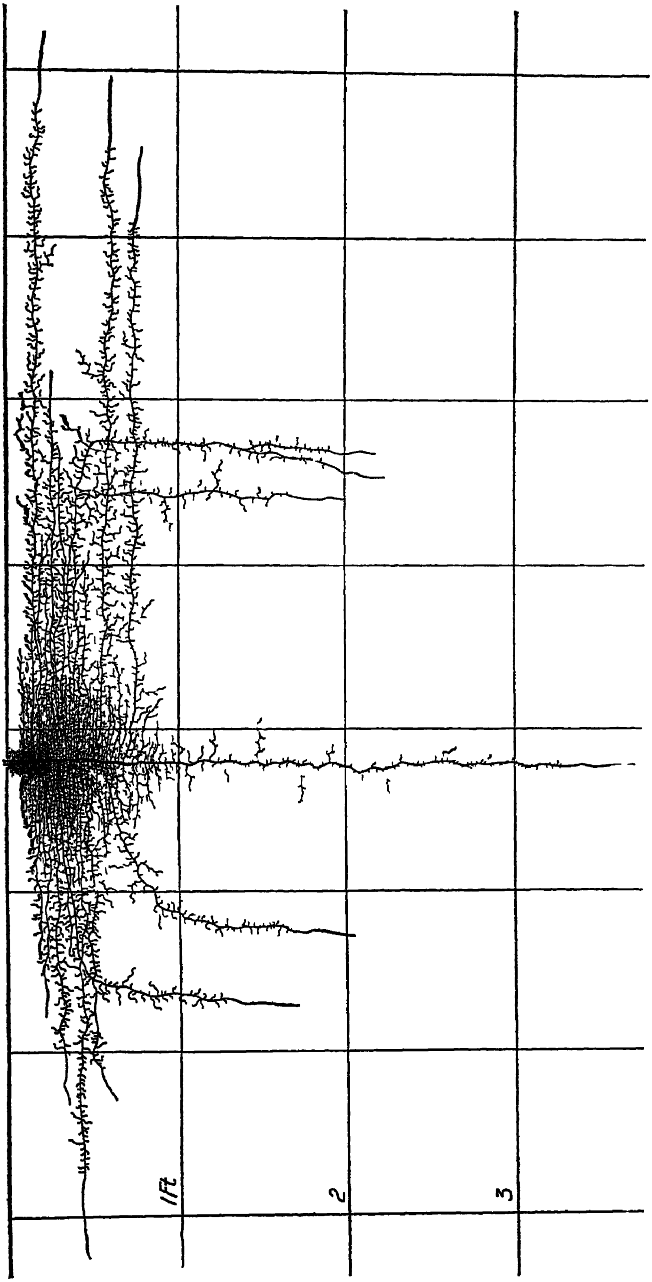


Fig 82 —Widely spreading root system of cucumber on July 27 The plant is 2 weeks older than that shown in Fig 81.

inches The thick, unbranched, turgid root ends showed that growth was taking place rapidly The smaller and shorter branches varied from 4 inches to 2 5 feet in length The usual rate of branching on all of the roots was 4 to 5 per inch but on

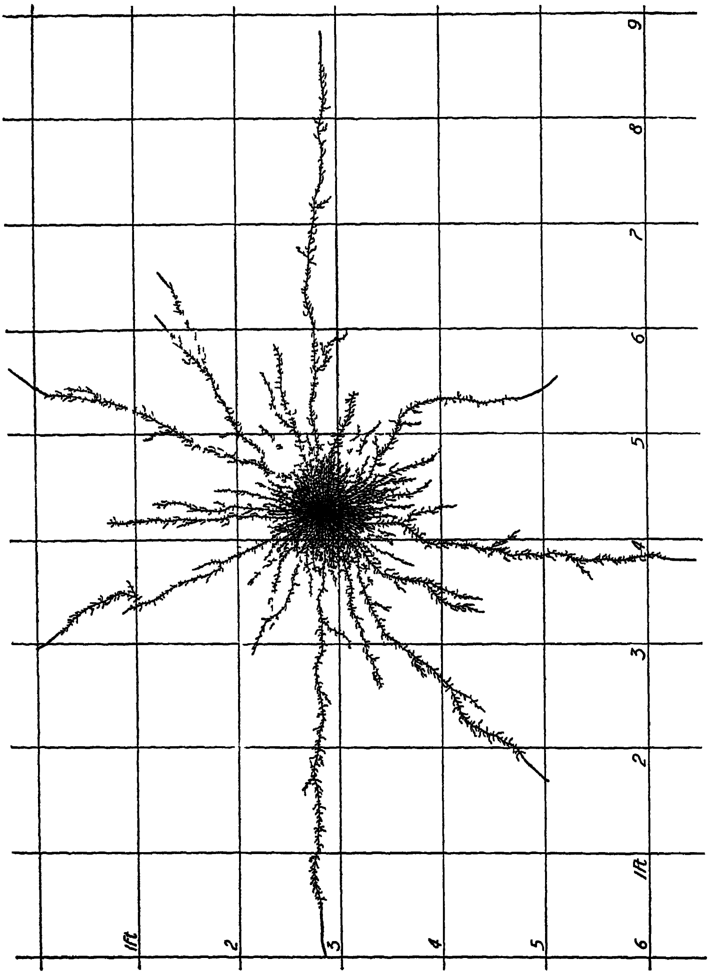


FIG 83 —Surface view of the widely spreading roots of cucumber on July 27, showing their appearance upon the removal of the surface 8 inches of soil Compare with Fig 82

some an average of 10 branches per inch was found The branches were mostly 1 inch or less in length and poorly or not at all rebranched But not infrequently branches 2 to 4 inches long occurred which were well furnished with laterals These quite

as frequently ran upward toward the soil surface, sometimes ending just beneath it, as horizontally or downward The main laterals sometimes forked and gave rise to two rather equal branches Only rarely did a main branch take an obliquely downward course, although a few of the horizontal roots, after growing away from the plant for some distance, turned abruptly downward These, like a few of the longer main branches from the horizontal laterals, which also ran straight downward, reached depths of 2 feet or more (Fig 82) Some of these sublaterals from the main branches were 1 5 to 2 feet long and well clothed with branch rootlets

All of the roots, whether old or young, had the characteristic taste of the cucumber fruits and, like many other vegetable crops, could be identified by this character alone

Figure 83 shows the roots as they appeared upon the removal of the surface 8 inches of soil This gives a better idea of their wide distribution on all sides of the plant At this stage of development, the roots spread over three times as far as the vines Clearly cultivation that extended beyond a depth of 1 inch would have been distinctly detrimental at this stage of development

Maturing Plants—A final examination was made Aug 22 when many of the earliest fruits were fully grown and younger fruits and blossoms occurred in abundance The spreading vines, some of which had four to six branches, measured 4 to 5 8 feet in length The leaves, a few of which were beginning to dry, averaged 5 5 by 6 inches in size, some of the larger leaf blades being 9 inches long Thus a very great photosynthetic area was exposed for transpiration

The taproots had not increased in depth and the deeper portions showed considerable deterioration In fact most of the branches on the taproot below the 18-inch level were also withered That some development had taken place here, however, since the last examination, was shown by the fact that a few roots had reached lengths of over 2 feet before decaying But the main increase in absorbing surface had occurred in the formerly shallow portion Some of these large laterals had increased their extent to a total distance of 7 feet where they ended in the surface foot of soil Thus the roots kept pace with the spreading vines

The behavior of these laterals may be illustrated by a single, typical case One branch left the taproot at a depth of 2 5 inches It ran outward for 19 inches, where at a depth of 6 inches, it gave

rise to a vertically descending branch which reached the 3-foot level. Two inches further on its course two more large, vertically descending branches arose. Both of these were traced to a depth of 40 inches. A few inches beyond the main root forked into two rather equal branches which continued their horizontal course and ended 50 and 52 inches, respectively, from the taproot.

This root behavior gives the clue to a second way in which the absorbing area was increased, *i.e.*, by the production of rather numerous, vertically descending and deeply penetrating branches. From 1 to 3 usually occurred on each of the 8 to 10 largest laterals. Some of the less extensive main branches also produced them. Moreover, not infrequently the main root itself turned downward, a behavior already indicated at the earlier examination. In this manner moisture and nutrients to depths of 3.7 feet were secured. Sometimes the deeply penetrating roots divided into several rather equal branches 3 to 4 inches long. These with their laterals formed an efficient absorbing network. All of the new roots were well branched; in fact over the entire root system branches were longer than before and laterals of the third and fourth order much more abundant. Intermingled with the main branches from the taproot were very numerous smaller ones, 12 to 26 in a single inch. These were most numerous just below the soil surface. Being profusely rebranched, they formed a close absorbing network.

Summarizing, the taproot had grown somewhat since the July examination but was now considerably deteriorated. The surface-absorbing portion of the root system had extended its area from 3 or 4 feet (July 27) to 6 or 7 feet on all sides of the plant. Owing to longer and better-branched secondary laterals, the surface foot of soil was more thoroughly occupied. By the production of numerous, long, vertically penetrating branches reinforced by the downward penetration of some of the formerly horizontal roots, all of which were well clothed with absorbing rootlets, the second, third, and to some extent the fourth foot of soil were also ramified. In this way the absorbing area had kept pace with the vigorously growing tops.

Summary.—The cucumber, upon germination, soon develops a strong taproot. This penetrates downward at the rate of 1 inch per day and extends into the third foot of soil. Numerous horizontal laterals develop rapidly and spread widely in the surface 8 inches. After 4 weeks some of these exceed the taproot

in length When the vines begin to run, the roots make a vigorous growth Surface roots become extremely abundant They quite fill the soil within a radius of 18 to 24 inches, the longer ones extending outward 3 to 4 feet With their numerous branches they form the shallower portion of the root system The rather poorly branched taproot, extending into the fourth foot of soil, represents the deeper part The turning downward of some of the superficial roots or their branches foreshadows a rather marked, later, deeper rooting habit Maturing plants, scarcely 10 weeks old, have vines 4 to 6 feet long and a surface root system quite as extensive, having a maximum spread of 7 feet The main laterals are not only exceedingly numerous but profusely rebranched in such a manner as to thoroughly occupy the soil The taproot has not increased in depth, and the deeper portion, which never becomes extensive, has more or less decayed But the soil to a working depth of 3 7 feet is filled with an efficient absorbing system composed of the vertical ends of some of the surface branches or their well-branched, vertically descending laterals This portion of the root system greatly extends the absorbing area and is an efficient protection against drought

Other Investigations on Cucumber —Cucumbers of the White Spine variety were grown in very fertile garden soil at Geneva, N Y The taproot extended perpendicularly to the 18- to 24-inch level when it became too delicate to trace Many larger roots extended 48 inches horizontally The laterals were numerous, nearly filling the soil to a depth of 12 inches The roots extended horizontally as far as the vines The root system was more concentrated where the subsoil was fertilized with barnyard manure [11]

Experiments have been conducted at Odessa, Russia, in which plants were grown in the field but in such a manner that their rate of growth could be observed from time to time During the first month the root growth was found to be rather weak but, in remarkable contrast to other plants examined, *viz* , beans, peas, and beets, the vertical growth of the cucumber was exceptionally vigorous with the inception of the flowering period Plants from seed sown Apr 13 had, at the beginning of the flowering period on May 31, a root depth of 20 inches and a spread of horizontal roots of 12 5 inches A month later the maximum root depth of 41 5 inches had been reached The lateral spread was 16 5

inches but upon maturity of the plants it had been increased to 33 inches [123]

Further experiments at Saratov, Russia, confirm the authors' results in regard to the nature and extent of the root system [76]

Root System in Relation to Cultural Practice —A study of the root system explains why the soil should be well drained but retentive of moisture Light soils that warm quickly are favorable for rapid root and vine development but the late crop is likely to suffer from drought It appears clear why on heavier soils the yields are usually larger and the bearing period longer A compacting of a heavy clay during a wet year, through the tramping incident to picking, is distinctly detrimental to the roots This is reflected in poorer growth aboveground and in a decreased yield

The very rapid and extensive growth of the roots, largely in the surface layers of soil, indicates the need of favorable conditions in this portion of the substratum This is accomplished by early plowing and thorough subsequent cultivation Weeds are germinated and killed, water is conserved so that the seed will germinate even in dry weather, and the soil is brought into good physical condition It remains loose and mellow and does not form a crust as is frequently the case when freshly plowed Moreover, nutrients are made more readily available as a result of better aeration and the activities of nitrifying and other bacteria are promoted In such a substratum the roots find conditions very favorable for growth Poor soil preparation and low fertility result in slow development and the plants may be overtaken by drought before the root system has spread widely and deeply The concentration of the root system largely in the surface soil layers also helps to make clear why a rich soil is essential to good yields

To get an earlier crop in the North and also to prolong the growing period, cucumbers often are started in the greenhouse or hotbed and transplanted into the field The method employed results from the fact that all cucurbits are transplanted with difficulty if the root system is disturbed This is due to certain root characters, such as early loss of absorbing power by the older roots and the slow rate of new root formation (p 119) To prevent disturbing the roots and thus checking the growth of the plants, the seeds are planted in soil that is well compacted into pots, plant bands, small boxes, etc , or transplanted from flats

into these when the plants are very small When they are set into the field, care is taken so that the whole mass of soil adheres to the roots and transplanting is accomplished without disturbing them

After the plants are transplanted, deep cultivation near them is desirable to loosen and to aerate the soil and thus to promote a rapid root growth Plants started in the field should not be cultivated close to the hill since the root system, which spreads with great rapidity, is very likely to be injured The common practice of frequent shallow cultivation until the vines cover the ground would seem to be quite in accord with the best root growth But the cultivation must be very shallow, otherwise the long, horizontally spreading roots will be severed and the yield correspondingly reduced It should be kept clearly in mind that the roots spread more widely than the vines, sometimes, as at the beginning of blossoming, three times as far In fact the practice of shallow cultivation needs especial emphasis in the growing of all kinds of cucurbits Experimental work along this line is needed Since the hills are widely spaced, moisture may be conserved between them by proper tillage By the time the vines have spread widely, however, the roots have similarly extended their territory The vines prevent water loss from the surface soil by shading and the roots by vigorous absorption Thus it would seem that if weeds were kept out, further cultivation would be unnecessary

CHAPTER XXX

MUSKMELON

The muskmelon (*Cucumis melo reticulatus*), usually known as cantaloupe, is a coarse, trailing vine of tropical origin and consequently requires a fairly long, warm season for its development Although not as easily grown as most vegetables, it is a popular one, and is to be found in many home gardens It is grown commercially for home use over a wide range of territory in the United States, and there are also numerous large regions producing it commercially where muskmelons are grown on an extensive scale In fact the industry is fairly well distributed over the entire United States The crop is usually grown from seed planted in the field but, when produced in regions with a short growing season, a common practice is to start the plants in greenhouses, hotbeds, or cold frames[10]

Seed of the Rocky Ford Muskmelon was planted at Norman, Okla , Apr 19 The hills were placed 6 feet apart in rows 7 feet distant Several seeds were planted in each hill but when the plants were well established they were thinned to one plant per hill by cutting out the weaker plants Cultivation was shallow so that the roots would not be disturbed

Early Development.—The plants grew slowly through May and by the twenty-fourth the vines were but 2 feet long with two to three short branches only 3 to 6 inches in length Flower buds were appearing

Like various other cucurbits, in their early development they had strong but rather shallow taproots and numerous strong, horizontally spreading laterals The taproots were rather thick (5 millimeters near the soil surface but tapering to 2 millimeters at a depth of 1 foot) and extended to a depth of about 18 inches Usually about 4 roots 3 millimeters in diameter ran horizontally 18 to 36 inches This, it may be noted, exceeded the spread of tops Both the taproot and its branches were white in color, somewhat fleshy, and had a characteristic spongy appearance The longest laterals occurred at a depth of 4 to 12 inches From

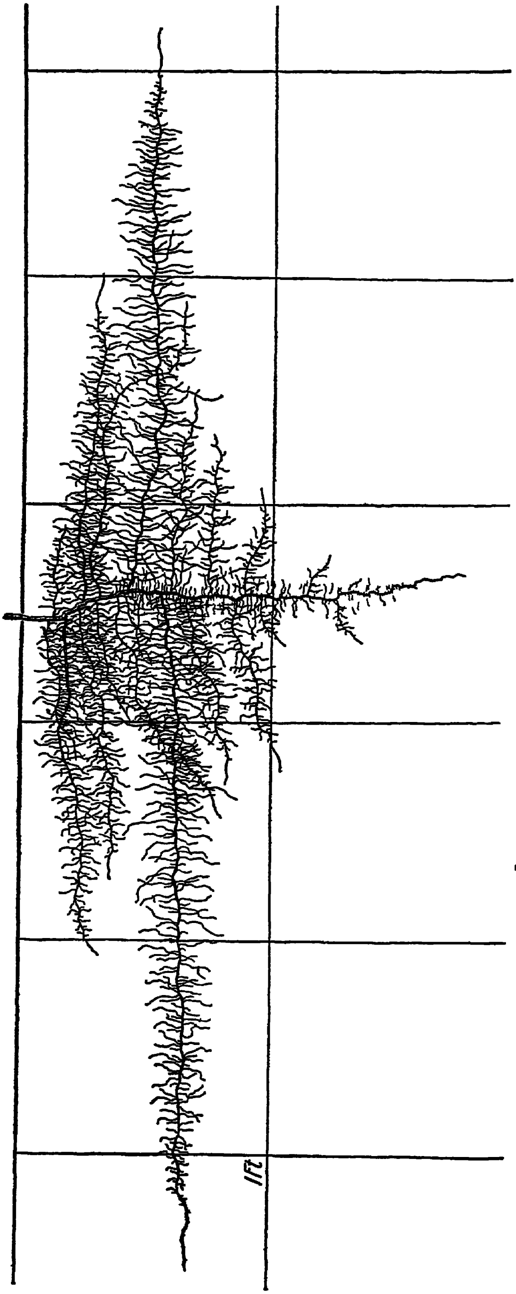


FIG. 84.—Rocky Ford muskmelon 35 days old

12 to 14 horizontal laterals 5 to 16 inches long were also found (Fig. 84). Shorter rootlets were so abundant that every inch of the taproot, except just below the soil surface and again near the tip, had 6 to 12 branches. Branching on all but the shorter laterals occurred at the rate of 4 to 6 rootlets per inch. Many of these on the older roots reached lengths of 2 to 3 inches but at this stage of development none were rebranched.

Half-grown Plants.—Root development was again examined June 11. The vines had grown vigorously since the last examination and some were 9 feet long. On plants of average size the taproots were 7 millimeters in diameter and penetrated downward, usually with kinks and curves, to a depth of about 25 inches. No change in the general root habit had taken place. About 7 of the horizontal laterals, however, had spread very widely (maximum, 57 inches). The others were by no means so well developed. Within a distance of 18 inches from the base of the plant, in addition to the abundant simple branches, 3 or 4 laterals per foot were usually 5 to 8 inches long. These were furnished with secondary branches 0.2 to 1.5 inches long at the rate of 6 to 8 per inch. Beyond 18 inches the longest branches on the larger roots did not exceed 4 inches in length and, like the abundant shorter laterals, they were quite unbranched. The thick, glistening white, turgid root ends were 2 millimeters in diameter. They were elongating so rapidly that usually several inches of root ends were quite unbranched. In fact branches 0.5 inch long were not usual until a distance of 6 inches from the root tip was reached.

All of the rapidly growing main roots (except the tips) and their younger branches were exceptionally well clothed with root hairs. The yellowish color of the older portions of the roots near the base of the plants indicated the loss of absorbing power in this region.

Maturing Plants.—The muskmelon had passed through its period of most vigorous growth by July 24, when a final examination was made. The vines were over 12 feet long. Fully grown fruits were ripening but on other parts of the vines blossoms and fruits in various stages of development were found. As in the earlier examination, the root system consisted of two rather distinct parts, a poorly branched deeper portion of the taproot and a wonderfully developed absorbing system in the surface foot of soil.

The taproot had pursued a rather tortuous course to a maximum depth of 45 inches Below 2 feet the branches were short, although rather abundant, and only fairly well rebranched Between the 12- and 24-inch soil levels a few larger branches, often obliquely descending but not extensive, supplemented the smaller, shorter ones As a whole, however, this deeper portion of the root system, as in other cucurbits, was clearly overshadowed by the extensive superficial root development

In the surface 4 to 8 inches of soil eight strong roots with diameters from 5 to 10 millimeters originated These roots pursued very devious courses in the fertile, moist soil, approaching or growing away from the soil surface through distances of 2 to 5 inches but having their whole course in the first foot of soil A usual depth attained was about 6 to 8 inches Some of the roots had a maximum lateral spread of over 15 feet although the roots were actually much longer Large laterals sometimes 4 to 5 millimeters in diameter arose at irregular intervals These diverged usually at wide angles from the main root but like it pursued a pronounced horizontal course Frequently, these reached lengths of 5 to 9 feet A single root sometimes gave rise to as many as eight major branches

In addition to the 8 major surface laterals 17 others were found arising from the four sides of the taproot in the surface foot of soil These varied from 1 to 3 millimeters in diameter and 2 to 7 feet in length They too gave rise to very numerous branches The more vigorous of these branches were repeatedly noticed to pursue a horizontal course Numerous others, of lesser diameter (about 0 5 millimeter) grew upward to within 1 inch of the soil surface or extended into the deeper soil, occasionally to a depth of 2 or more feet

On the first 3 feet of the major roots absorbing laterals were sparse But large branches, abundantly furnished with absorbing laterals, extended in all directions, some vertically downward to a depth of 2 feet Even beyond 3 feet a few vertical branches extended well into the second foot of soil Farther outward on the horizontal, main branches absorbing rootlets became increasingly more numerous Some extended vertically upward to very near the soil surface For example, in addition to the longer branches already described, laterals 1 to 4 inches long occurred at the rate of 6 to 12 per inch On the younger portions

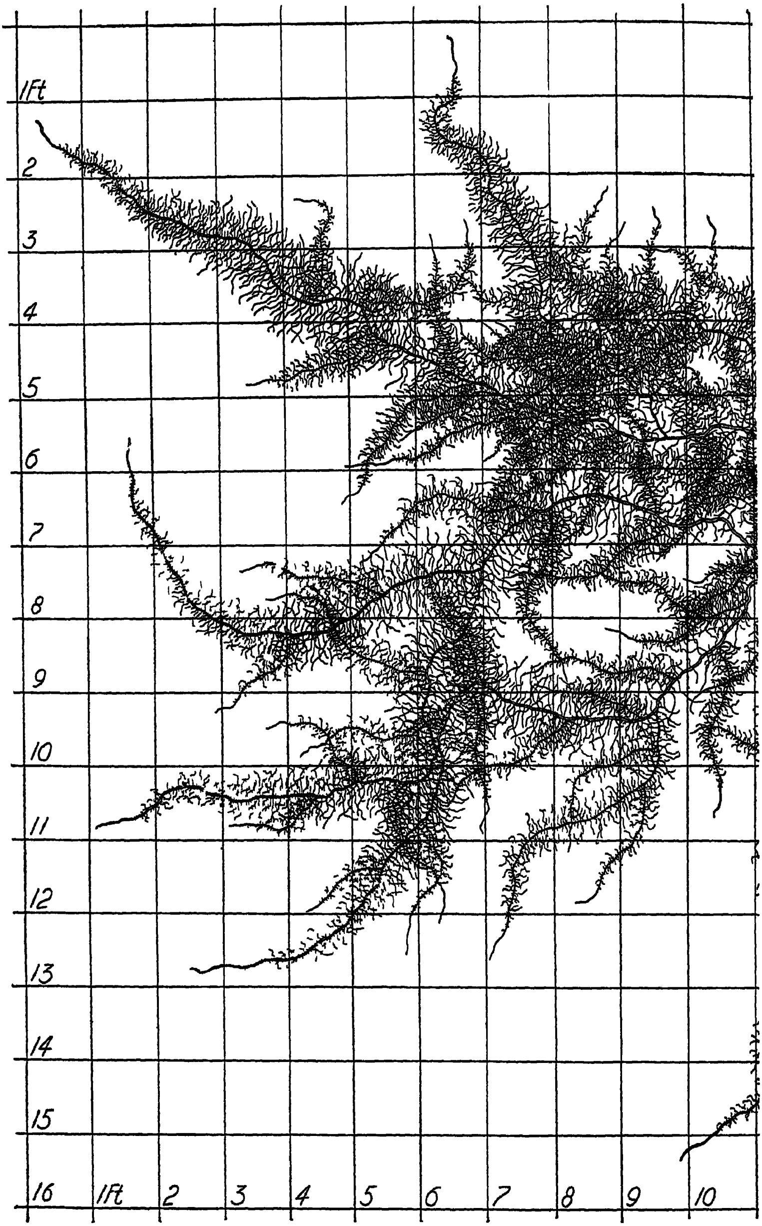
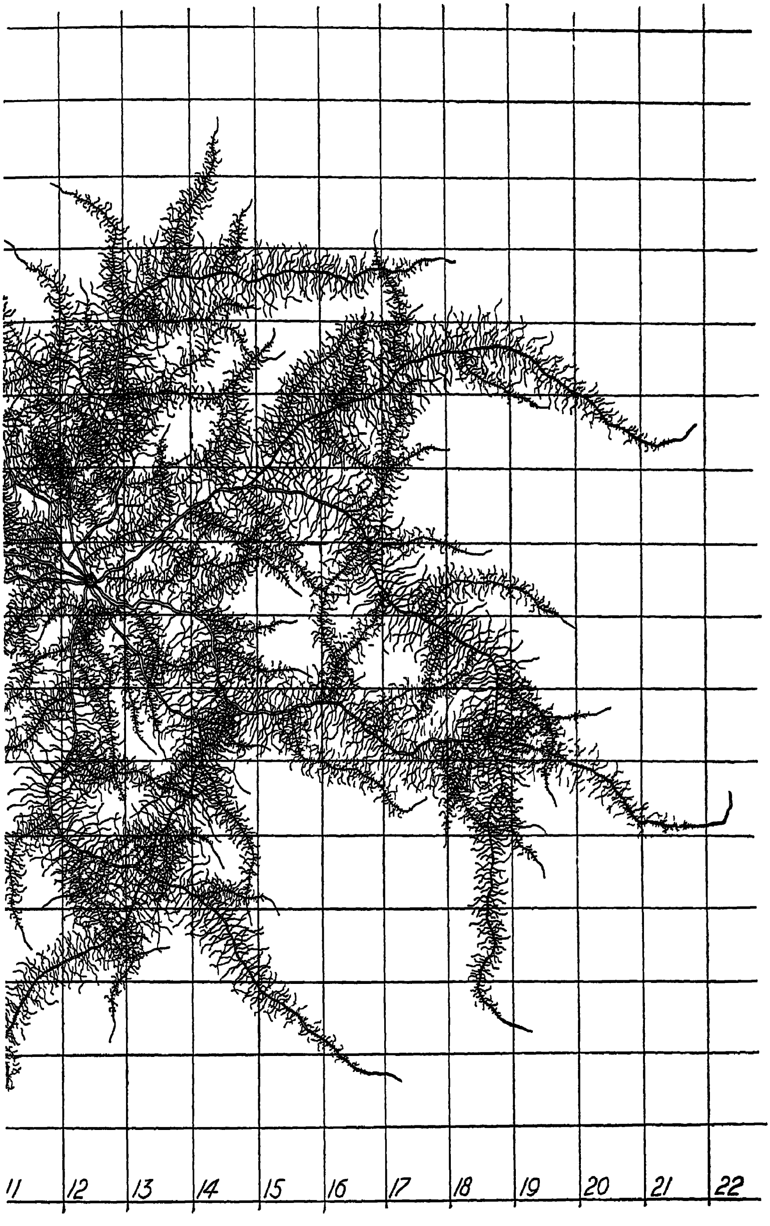


FIG 85—Surface view of the root system of muskmelon on July 24, 14 weeks
roots were still



after planting Only the larger main roots and their branches are shown The
growing vigorously

of the roots, which were still growing vigorously, the branches were only 1 or 2 inches in length. The turgid, shining, bare root ends maintained a diameter of 2 millimeters and were still in a vigorous state of growth. A clear conception of this wonderfully intricate root system may best be obtained by a study of Fig. 85. But even here only the larger main roots and their branches are shown. Nodal roots were not permitted to develop since the vines were loosened from the soil and laid aside in the process of cultivation.

Summary.—The muskmelon, like the closely related cucumber, has a root system consisting of a very extensive shallow portion and a poorly developed deeper part. Just as the vines and transpiring area of the muskmelon are far more extensive than those of the cucumber, so too the root system is much larger. When the vines are 2 feet long, the taproot is only 18 inches deep, but the longest of the numerous horizontal roots extend outward 3 feet. Long, simple, secondary laterals are numerous. Half-grown plants, with vines 9 feet long, have taproots 2 feet deep. Six to eight of the horizontal laterals make a marked growth, spreading widely, some to 4.5 feet. These with their very numerous long branches, all densely furnished with smaller laterals, fill many cubic feet of surface soil. Nearer the plant the root masses are most abundant. On maturing plants, but where tops and roots are still growing, root extent is even greater. The taproots, now quite well branched in the second foot of soil, penetrate beyond the 3.5-foot level. The strong surface roots pursue their tortuous outward course, some to a distance of 3 feet beyond the 12-foot vines. Branches from these, 2 to 9 feet long, are also superficial. Many other long primary laterals are likewise clothed with delicate branches of considerable length. Thus the surface soil, many feet on all sides of the plant, is thoroughly ramified by a wonderfully extensive root system with an enormous absorbing area. It is equipped to furnish abundant supplies of water and nutrients to the very extensive aboveground parts.

Other Investigations on Muskmelon.—Roots of the Oblong Netted muskmelon were examined at Geneva, N. Y. The plants were grown in a clay loam soil with a depth of 6 to 10 inches below which occurred a tenacious subsoil of gravelly clay. The plant, examined in the middle of September, had not made a very vigorous growth.

The roots were for the most part very shallow in the soil, though we traced a single one to a depth of 16 inches. The main roots extended horizontally and at a depth of 3 to 5 inches below the surface. We traced one of these a distance of 3 feet, which was as far as the longest stem reached. Short, fibrous roots are, however, quite numerous at a depth of 8 or 10 inches. It thus appears that the muskmelon is a shallow-rooting plant but its roots draw nourishment from a large area.[43]

During another season at the same station:

> The roots of a plant of the Montreal Nutmeg were washed out Sept. 7. The taproot extended perpendicularly only about 4 inches, then it turned nearly at right angles, descending only gradually as it progressed. The main horizontal roots lay 2 or 3 inches below the surface, and one of these was traced to a distance of 5 feet from the base of the plant, which is further than any of the runners extended. One root ran horizontally a distance of 15 inches, when it suddenly turned downward, and was followed for fully 2 feet. At the depth of 20 inches, it branched much in the compact clay.[44]

Examination of the root system of muskmelon at Saratov, Russia, was made on Sept. 12, when the plants were mature. The main mass of roots was found in the surface 16 to 20 inches of soil. The lateral roots of the first order were found to be longer than the taproot and spread in all directions. Each of these laterals had a large number of well-branched roots of the second, third, and higher orders. These formed an interlacing root network with a diameter of many feet. On sandy soil the same species had roots of a larger diameter. The length of the roots approximated that of the vines.[76]

Root Habit in Relation to Cultural Practice.—The roots of muskmelon thrive best in a well-drained and, consequently, well-aerated, humus-filled soil that becomes warm early in spring. Experience has shown that any fertile, friable, well-drained soil is satisfactory provided it will maintain or is furnished with an abundance of soil moisture from the time the plants start until the beginning of the ripening period. Good soil structure, which should not be too loose, is promoted by careful, deep plowing early in the spring and followed by repeated tillage so that the soil becomes well settled before planting. The inability of the roots to withstand water logging and consequent poor aeration has resulted in the practice of "bedding" the soil. This is essential on low, river-bottom or alluvial soils where the water table is near the surface, where excessive rains

frequently occur, and where the crop is grown under irrigation A common method is that of plowing the land in beds usually 5 to 7 feet in width with open furrows between the beds to permit rapid drainage [10]

As shown by root as well as top development, the muskmelon is a rapidly growing crop and requires an abundance of nutrients It is fully as necessary, however, that the soil be mellow and well supplied with organic matter Placing well-rotted manure about 6 inches deep under the hill and within easy reach of the roots is an old and excellent practice To accomplish this the field is furrowed out both ways so that the furrows cross about 4 to 6 feet apart where the plants are to be grown A quantity of well-rotted manure is placed into the bottom of the furrows at the intersections and is often thoroughly mixed with the soil Soil is then compacted over the manure so that the seeds and roots will not suffer from lack of moisture by reason of large air pockets in or about the mass of manure Manuring in the hill and thus giving the plant a vigorous start, has been found to be far superior to broadcasting the manure unless a very large quantity of it is used Where large amounts of manure are available, the roots obtain an abundant supply of nutrients at all times by a rapid extension of their absorbing system [91, 92]

The proper method of planting is such that it not only insures a good stand but permits thinning without disturbance to the roots of the remaining plants Hence, when planted in hills care is taken to space the seeds some distance apart, this, of course, also applies to drills Because of the ravages of insect enemies the plants are often left unthinned until well established Since there is danger of seriously disturbing the roots, the excess plants are often cut at the ground line instead of being pulled out

When plants are not started from seed in the field, provision must be made for removing the soil mass undisturbed with the roots of the transplants Hence, the use of pots, dirt bands, or pieces of inverted sod Nor can they be grown more than 4 to 5 weeks before transplanting [10]

Cultivation should be performed with a thorough regard to root development A deep root system may be promoted by loosening the soil to a good depth about the young plants provided the root ends are not injured As the root system develops cultivation should be farther away from the plants It should be shallow but frequent and continued until the vines cover the

soil and the roots thoroughly ramify it When this stage of development has been reached, it would seem that further tillage, although practiced by some growers who lay aside the vines, would do more harm than good

The relatively shallow position of the root system makes it entirely clear why light, frequent irrigations, which wet the soil only throughout the root extent, are better than soaking ones given at longer intervals [100]

CHAPTER XXXI

WATERMELON

The watermelon (*Citrullus vulgaris*) is a coarse, trailing, annual herb with branching tendrils. The widely spreading vines often reach lengths of 12 to 18 feet and the roots spread quite as far as the vines. It is a native of tropical Africa and requires a long and relatively hot season for its best development. It is grown most extensively in the South, where it is an important field and truck crop, and also in the central states. Early-maturing varieties are grown in the North, however, the growing period frequently being lengthened by starting the plants under protection for a few weeks before setting them in the field. Since the plants require much room, they are not so common in home and market gardens as most other vegetables. The citron is a hard and white-fleshed race of watermelon.

Watermelons of the Kleckley Sweet variety were planted at Norman, Okla., Apr. 19. Several seeds were planted in each hill. The hills were 6 feet distant in rows 7 feet apart. When the seedlings were well established all but the most vigorous one of them were removed from the hill.

Early Development.—The first excavating was done May 20. The plants had made rather slow growth and were just beginning to "vine." Each had three or four vines varying from 3 to 12 inches in length.

The taproots were about 5 millimeters in diameter and tapered to 2 millimeters near their ends at a depth of about 15 inches. One taproot forked dichotomously at a depth of 10 inches, the two branches diverging widely in the more compact subsoil. Horizontal branches began to appear 2 inches below the soil surface. These averaged about four per inch of taproot. None exceeding 4 inches in length occurred below the 12-inch soil level. Four of the larger ones were 2 millimeters in diameter and pursued a somewhat devious course to distances of 26 to 38 inches from the base of the plant. Except on the last 3 inches of these white, fleshy roots, laterals occurred at the rate of four to six per inch. These laterals were rather uniformly 0.5 milli-

meter thick and 2 inches long, they were entirely unbranched They grew in all directions but usually at right angles to the main root The smaller branches from the taproot varied from less than 1 inch to 2 feet in length Otherwise they were very similar to the longer ones

The roots rather thoroughly occupied the 8-inch furrow slice to within 1 or 2 inches of the surface but seemed to avoid penetrating the compact deeper soil The root habit was so similar to that of the muskmelon that no drawings were made

Half-grown Plants—A second examination was made June 10 Each of the thriving plants had several vines 4 to 8 feet long The general habit of the root system had not changed The chief difference was an increased lateral spread to a maximum distance of 5 feet The depth of root penetration had increased only slightly (to 24 inches) On the first foot of taproot about 12 laterals per inch arose On an average, 1 of these had developed strongly, 3 were of medium length, and the rest were small Seven short branches per inch, as an average, were found in the second foot of soil In fact little absorption was occurring at this level Small laterals were not abundant on the first 12 to 18 inches, *i e*, the oldest portion of the larger roots But elsewhere, as on the shorter laterals, rootlets about 2 inches long occurred at a rate of 6 to 12 per inch Tertiary branches were entirely absent At this stage of development, however, a differentiation in the size and length of the secondary branches was taking place Approximately 1 root per inch was making a more vigorous growth than the others Many of these later developed into strong laterals

It is of interest to note that the muskmelon, planted at the same time had vines quite as long as those of the watermelon, taproots of the same length, and also a lateral spread of roots of approximately 5 feet

Mature Plants.—The period from June 10 to July 26 was one of very rapid growth in the development of the watermelon The vines, which now intermingled between the hills, were 15 to 18 feet in length Fully grown fruits were abundant Some had been ripe for a period of 10 days

The taproots were 15 millimeters thick near the ground line, 2 5 millimeters in diameter at a depth of 12 inches, and some penetrated to the 45-inch level As is common among the cucurbits, the deeper portion of the root system was relatively

poorly developed Below 12 inches only short horizontal and obliquely or vertically descending branches were found These occurred at the rate of only one to four per inch Below 2 feet the laterals did not exceed 3 inches in length, the last 4 inches of root end being free from branches

The surface-absorbing system had made a truly remarkable growth It was, in general, similar to that of the muskmelon but very much greater in extent It consisted of 24 main roots and their very extensive branches The four largest of these had diameters of 1 centimeter at their origin and tapered to about 4 millimeters at a distance of 15 feet from the plant A diameter of 2 millimeters was maintained to their tips They ran 18 to 21 feet from the base of the plant Thus the root extent exceeded that of the vines The remaining roots were 1 to 5 millimeters thick and varied from 3 to 16 feet in length No small absorbing laterals were found on the taproot nor on the branches near it In fact the larger branches were devoid of rootlets throughout the first 12 to 24 inches of their course except for the 8 to 16 rather strong branches which here originated Large secondary branches 3 to 5 millimeters thick were likewise bare for short distances Otherwise a wonderfully well-developed network of rootlets filled the surface foot of soil, many laterals extending far into the second and sometimes entering the third foot

Major laterals arose from the main branches in large numbers, usually one or more every 1 to 3 feet They were most abundant in the first 10 feet from the base of the plant They diverged at various angles with the parent root but pursued a generally outward direction Such laterals, 6 to 10 feet long, were frequent Beyond 15 feet the branches were usually 8 inches or less in length and mostly unbranched Although the main roots and their numerous horizontal branches were confined almost entirely to the surface foot of soil, rather numerous, vertically descending branches extended into the second foot or beyond The surface soil was extremely well ramified with these main roots and their profuse sublaterals The latter were 3 to 4 inches long and occurred at the rate of about eight per inch Branching in the deeper soil was less pronounced

The vines were laid parallel to the row from time to time during the process of shallow cultivation and consequently not allowed to root at the nodes

Summary.—The vines of the watermelon, which spread more widely than those of the muskmelon, are equaled in extent by the extremely elongated, shallow roots. Month-old plants, just beginning to "vine," have short taproots with long branches only in the surface soil. Among the very numerous, horizontal branches some are 2 to 3 feet in length. Long, simple, secondary branches are very abundant. Twenty-one days later the vines are 4 to 8 feet in length. Root depth increases to 2 feet, but only a small absorbing area is developed in the second foot of soil. The lateral spread has increased to 5 feet. Of the very numerous main laterals, about 12 make a most vigorous growth. Maturing plants have vines 15 to 18 feet long and a superficial root system similar to that of the muskmelon but much more extensive. It consists of about 24 main roots and their very extensive branches. A few extend outward 18 to 21 feet from the base of the plant. Major branches are abundant and minor rootlets almost innumerable. The surface foot is a network of roots. Numerous larger branches extend into the second and even the third foot of soil. These (with the short branches from the taproot, which is now 4 feet deep) quite thoroughly ramified the deeper soil but to a far less degree than the wonderfully developed surface root system.

Other Investigations on Watermelons.—A thorough study of the root system of watermelons and citrons at Saratov, Russia, gave results similar to those described. The seeds were sown the middle of May and root excavations were made in the middle of September when each plant had about four or five large, ripe fruits. The main root mass was found in the surface 16 to 20 inches of soil. The taproot, with a diameter of 23 millimeters, extended downward to a depth of approximately 3 inches before it began to branch. At this depth it was 15 millimeters in diameter and tapered to a thickness of only 1 millimeter at a depth of 41 inches. Here it was broken and the soil was so hard that the maximum depth was not determined. As the taproot penetrated the deeper soil, the number of laterals decreased. At depths of 27.5 to 31.5 inches only fine unbranched rootlets arose from the main root.

The most important lateral roots, 12 in number, originated between depths of approximately 3 and 7 inches. Most of them followed a wavy, horizontal course, which was found not to exceed a depth of 12 inches nor to approach nearer than 3 inches to the

soil surface These large, horizontal roots were generally longer than the taproot They spread widely in all directions as white, thin, whip-like branches, some having a length of 13 to 16 5 feet (maximum, 19 7 feet) and were almost as long as the surface vines (Fig 86) These laterals varied from 5 to 10 millimeters in diameter at their origin but tapered to a thickness of less than 1 millimeter at their ends Each of them had a very large number of well-branched rootlets of the second, third, and

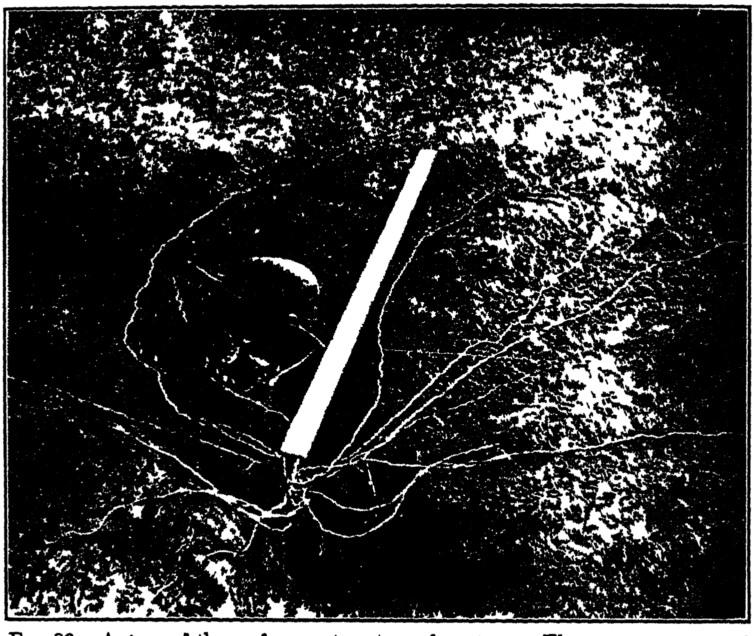


FIG 86—A view of the surface root system of a citron The main roots varied from 13 to over 16 feet in length (*After S Kartashova*)

higher orders Those of the second and third order were from 3 to 4 millimeters thick at their origin and all branched very extensively Some of the finest lateral rootlets were spotted with anthocyanin over small areas Altogether the roots formed a great network of long, rebranched laterals completely occupying a surface-soil area sometimes 26 to 32 7 feet in diameter [76]

Root Habits in Relation to Cultural Practice—Well-drained, warm, and fertile soil of good tilth and humus content furnishes the ideal environment for the very rapid and extensive growth of the roots of watermelons Like all cucurbits they are intolerant

of poor aeration Sandy loams are preferred and those with a clay subsoil are quite ideal, since they warm quickly and promote rapid growth but still retain moisture quite well for the shallow root system Indeed, good crops may be grown under semiarid conditions if proper precautions are taken to preserve the soil moisture Any soil for melons must be capable of being worked early in the spring The melons, once planted, grow so rapidly, if temperatures are favorable, that relatively few cultivations can be given after the plants show aboveground The strong development of the laterals in the several species of cultivated cucurbits becomes apparent early in the life of the plant Melons only 2 weeks old were found to have a taproot nearly 7 inches long and laterals 6 inches in length, the whole occupying a soil volume approximately 12 inches in width and depth [76] Hence, most of the soil preparation must be done before the seeds are planted As for muskmelons and other cucurbits, the soil should be thoroughly plowed and subsequently worked to form a deep, mellow, but rather compact seed bed It should be constantly kept in mind, in preparing and fertilizing the soil, that the seat of greatest root activity is in the surface 8 to 12 inches

In the South, commercial growers plow comparatively deep furrows 10 feet apart and small cross-furrows also 10 feet distant at right angles to the deeper ones About a peck of stable manure is put into the deep furrows, approximately half of it on each side of the intersection of the two furrows, allowing a space of about 10 inches on each side of the intersection to be bare of manure The seeds are then planted at each intersection and the developing root system soon extends into the richly fertilized area and the plants grow vigorously When the vines are about 2 feet long a dressing of readily available nitrogen fertilizer is applied [146]

The room occupied by the greatly spreading vines accounts for the wide spacing of the plants, *viz*, in hills 8 to 12 feet apart or 2 to 3 feet apart in drills 8 to 12 or more feet distant Fortunately this allows ample room for root development, although spacing has been empirical in so far as exact knowledge of root relations has been concerned The proper method of hill planting, as well as that of planting in drills, is favorable to easy thinning without disturbing the roots of the stronger plants left to grow. About a dozen seeds are placed over an area of a square foot Various insect enemies make the fate of the seedlings uncertain

so that thinning is delayed until they are well established Being spaced at some distance, the plants come up independently and it is easy to select the most vigorous individuals that are to remain in the hill To avoid disturbance to their roots in removing their neighbors, the latter are usually cut at the ground line rather than being pulled Experience has shown just what a study of the very extensive and thorough ramifications of the root system points out, *viz*, that with an average moisture supply a single plant per hill will succeed in producing as good a yield as two will [146]

Like other cucurbits, watermelons are transplanted with difficulty unless the roots are protected from disturbance by growing the seedlings in inverted pieces of sod, in pots, bands, or other containers Under such treatment they have the advantage of a longer growing season and better protection during establishment from insect enemies After a few weeks they are transplanted into the field without checking their growth

Watermelons respond to the usual benefits of cultivation if the root system is uninjured The objects of cultivation are to remove competing weeds and make a more congenial environment for root development Early tillage is beneficial in preventing crusting of the soil and subsequent difficulty in the emergence of the large cotyledons, in promoting better soil aeration, and in conserving moisture It should be understood that root growth often exceeds that of the vines and takes place simultaneously, the roots are near the surface and beneficial cultivation must be shallow

Pruning the vines, as with sweet potatoes (p 239), is a harmful practice and not in common use [9] Any injury to the food-making portion of the plant probably results in a diminished root growth and smaller fruits The common practice of pruning the smaller melons has a different physiological basis which is entirely scientific

CHAPTER XXXII

SQUASH

The squash (*Cucurbita maxima*) is a coarse, annual plant grown in practically all parts of the United States It has long, running, cylindrical stems which are somewhat prickly and hairy The stems are often 12 to 24 feet in length and root freely at the nodes They are nearly always grown from seed planted in the field and only rarely started under protection and transplanted

Seed of the Golden Hubbard variety was planted June 2, in hills 8 feet apart, at the rate of three seeds per hill

Early Development —When examined on July 13 the plants had each about 12 large green leaves, of which the blades were

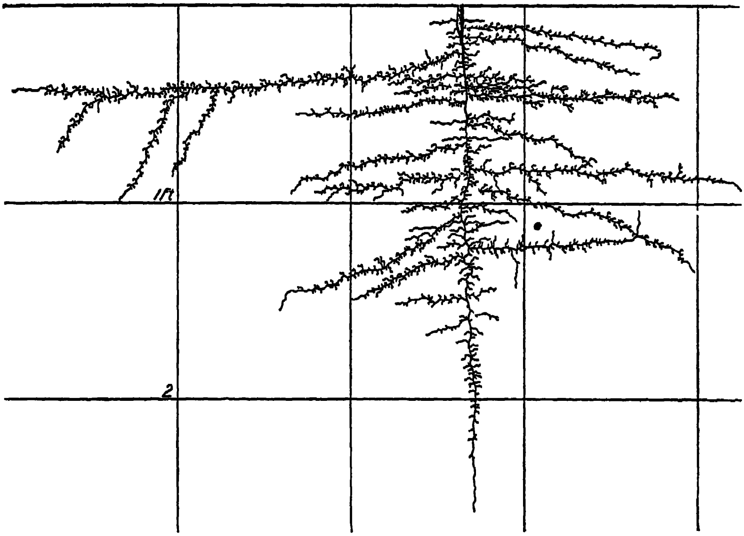


FIG 87 —Golden Hubbard squash 6 weeks old Note especially the widely spreading, shallow roots

3 by 5 inches in width and length, respectively, and 7 smaller ones In addition there were 4 or 5 discolored and dead leaves The plants were 8 inches high and had a total spread of 1 foot The leaf surface was 3 4 square feet

The root system was characterized by a strong taproot which, although zigzagging considerably in the hard soil, pursued a rather vertically downward course Maximum depths of 28 to 32 inches were attained The upper portion of the taproot was quite fleshy It was 7 millimeters thick near the ground line but tapered to a width of about 1 millimeter at a depth of 7 inches At greater depths it became quite thread-like Many long, mostly horizontal branches, the longest extending 30 inches laterally, and numerous short ones arose from the first 18 inches of the taproot (Fig 87) At greater depths the laterals were short and simple The last 2 to 3 inches were without branches In the surface 18 inches laterals occurred at the rate of five per inch, approximately two-thirds of them having a length less than 1 inch Most of these short roots were unbranched, some were poorly clothed with branches But on the longer branches laterals occurred rather regularly at the rate of five to eight per inch and varied in length mostly from 0 1 to 1 5 inches Some of the laterals on the older roots were again branched and the rather infrequent, long, secondary branches were well furnished with rootlets Thus the plant was rapidly developing a widely spreading and efficient absorbing system

As a whole the root system was slightly yellow in color, many of the smaller laterals were quite yellow but the younger portions were always glistening white

Midsummer Growth —Two weeks later a second examination was made, July 27, when the plants had just started to blossom The plant finally selected for detailed study had a total length of 6 5 feet The main stem had two branches and a total of 20 large leaves and 8 smaller ones Some of the largest plants possessed twice this number of leaves A very large transpiring area was presented by these leaves, since those of larger size had blades averaging 9 by 8 inches in length and breadth, and the smaller ones 4 by 4 inches, respectively The plants were making a very vigorous growth

The general root habit was of the same plan as that found 2 weeks earlier but much more extensive and elaborate The taproot, which was now 1 inch in diameter near the soil surface, penetrated downward in a very zigzag manner, tapering to 2 5 millimeters at a depth of 6 inches At greater depths its diameter was variable, decreasing to 1 millimeter but enlarging again to 2 5 millimeters only to become more slender at deeper levels

Near the root end, at 42 inches depth, it was 2 millimeters thick Not only had the root thus increased 1 foot in depth but also the former maximum lateral spread of 30 inches was now extended to 5 feet This was attained in the surface 8 inches of soil In fact, the chief growth was that of the laterals which had extended more widely, were more profusely branched, and had many more longer branches than before The degree of ultimate branching had also increased In regard to root habit in the deeper soil, *i e*, below 19 inches, it was almost identical with that in the second foot of soil at the earlier examination (Fig 87) A few of the deeper roots were decayed

Maturing Plants—A final study was made Aug 21 As usual several plants were examined but the one chosen for final study had two main vines One of these was 18 feet long and had five branches which were 3 to 7 feet in length The other was 21 feet in length with seven branches, the longest being 7 feet These vines were furnished with two rows of leaves The leaves averaged 1 foot in length and width Thus they presented an enormous transpiring area, probably losing several gallons of water in a single day The plants were in the late blossoming stage Nine fruits ranging from 2 to 7 inches in diameter were found

The squash plant in its later development is very much like certain native plants in having two rather distinct parts to its root system The one is largely superficial but widely spreading and the other spreads much less in the deeper soil where it may reach depths of 6 to 7 feet

The taproot and its deeper branches had made considerable growth and were extensively branched to the 6-foot level The branches were, however, relatively short so that below 2 feet not a very large volume of soil was occupied Some of these deeper roots were decayed at the tips

The most important, most active, and by far the most extensive portion of the root system occupied the surface soil Five to seven main shallow roots were common These were 4 to 7 millimeters in diameter and, although 10 to 14 feet long, usually ran at a depth of only 6 to 8 inches below the soil surface and were never found below the 12-inch soil level Even near their tips and after giving rise to numerous large branches, they were still 2 5 millimeters thick As shown in Fig 88, they spread on all sides of the plant and branched profusely except in the first 12 to 18 inches of their course in which branching was sparse

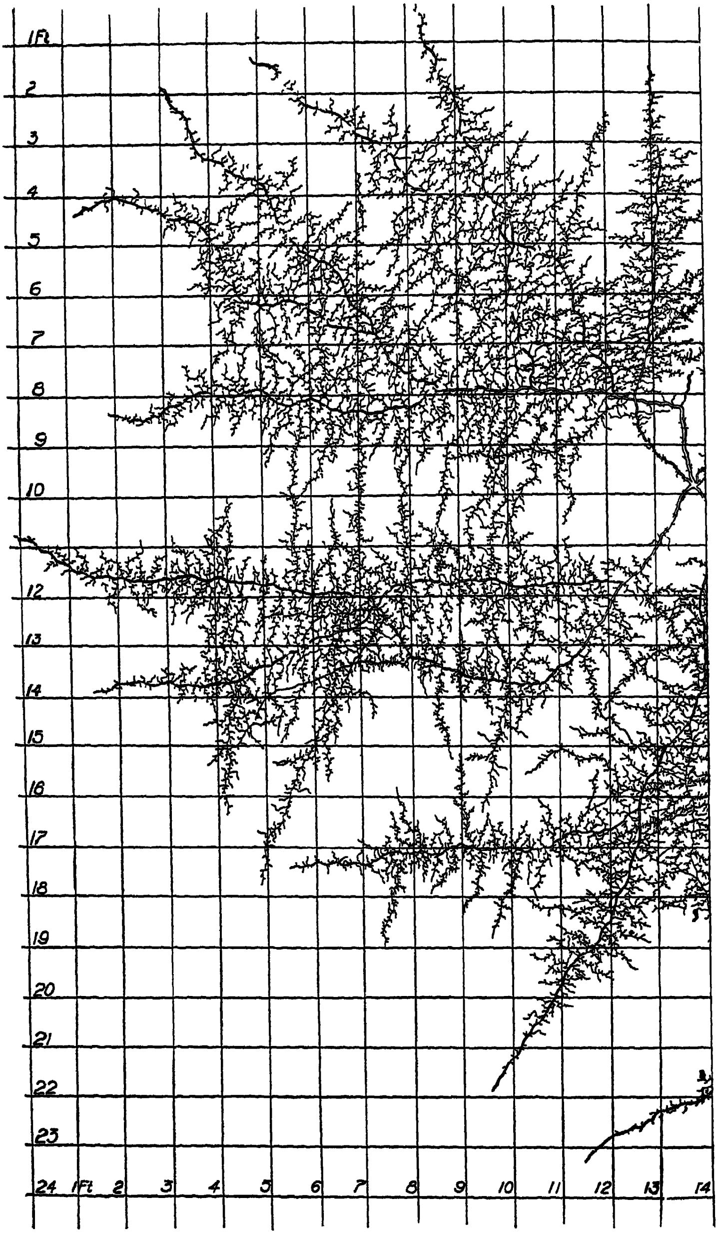
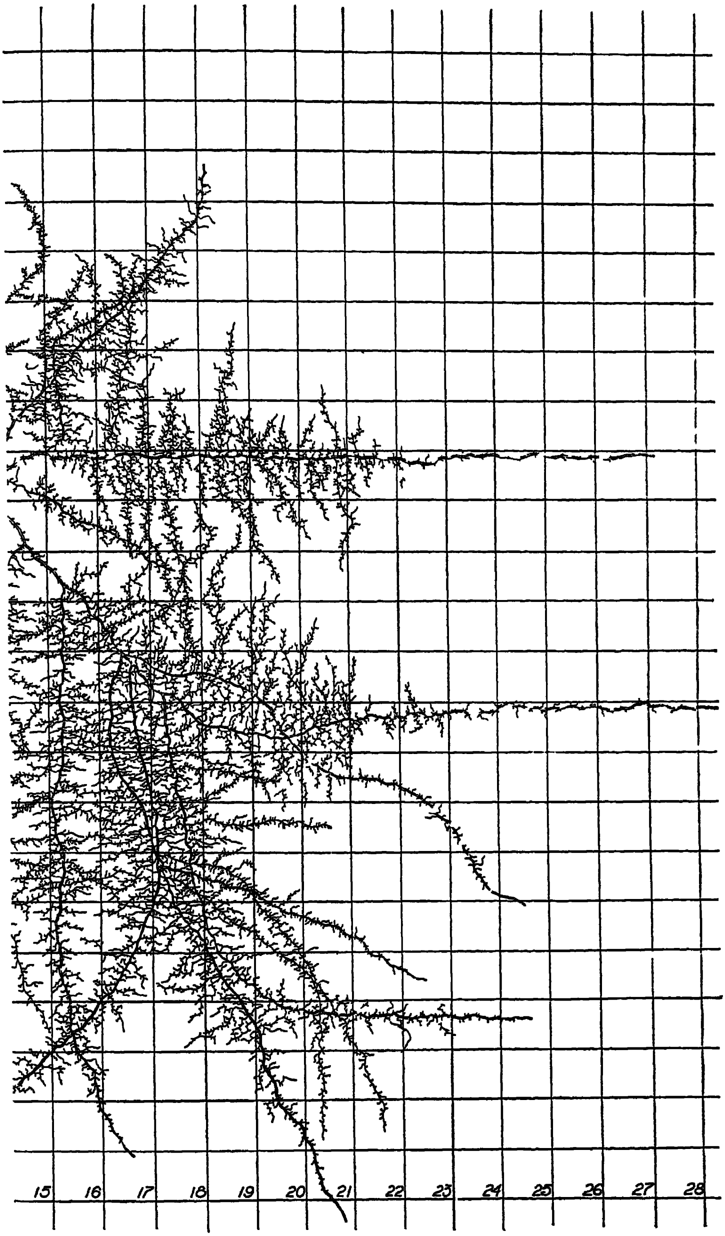


Fig 88—View of the root system of squash after the removal of the surface about 11 weeks old and the main roots were still



12 inches of soil The roots were excavated on Aug 21 when the plant was growing at the rate of nearly 2 5 inches per day

In studying the figure it should be kept in mind that all of the main roots were between depths of 4 and 12 inches and usually at the 6- to 8-inch level Sometimes they turned upward or downward abruptly (in which case they usually gave rise to major branches) but often ran for several feet at approximately the same depths These shining white, cord-like structures penetrating the mellow soil, the last 8 inches or more usually being free from both root hairs and branches, were striking objects in the dark-colored soil Frequently one could pull out five or more inches of root ends intact

The numerous main lateral branches on these widely spreading roots greatly increased the general root territory which later the sublaterals with their branchlets so thoroughly occupied Most of these roots had extended 12 feet and some to a distance of 17 feet from the hill Because of their curved and tortuous courses the lateral extent was usually much less than the actual root length Branches occurred at the rate of about four to five per inch For the sake of clearness only a part of the branches have been included in the drawing Most of them were 4 to 14 inches long and well rebranched Infrequently, long branches (1 to 2 per foot of root) occurred They varied from 2 to 8 feet in length and were rebranched profusely Practically all were found in the surface foot, sometimes very near the soil surface A few penetrated into the deeper soil but only rarely did they occur below the 2-foot level The roots were white and tough and rather readily excavated

Determination of the Rate of Growth —To determine how rapidly the roots were growing, the following experiment was performed The soil, 10 to 15 feet from the hill, was carefully examined until the uninjured, glistening white, smooth ends of the main roots were found The end of the root was immediately engaged in a loop of stout cord and the root quickly covered with moist soil The cord was tied to a small stake driven by the side of the root, the upper end of the stake being plainly visible and marking the position of the root when the soil was entirely replaced Several roots were marked in this manner on Aug 22 A week later an examination showed that some of the roots had made a growth of 17 inches in length, nearly 2 5 inches per day Great changes, moreover, had occurred The marked, unbranched root ends were now clothed with branches 0 3 to 2 inches long The diameter of the root had decreased to one-half or only one-

third of its former size Microscopic examination showed that this was due to a shriveling of the deteriorated cortex Root tips showed the beginnings (primordia) of lateral roots to very near the growing point These had grown through the cortex and elongated 2 inches and the cortex deteriorated in the moist soil all during a period of 7 days During a 2 weeks period some of the roots elongated 2 feet It is evident that the picture (Fig 88) is incomplete A mature root system fills the soil to a distance of 15 feet on all sides of the plant Seven hundred cubic feet of the richest soil may be occupied by the roots of a single plant How thoroughly the soil must be ramified in a field of corn where squash or pumpkins are growing among the corn! There must be keen competition for water and nutrients unless the corn at this season is depending more largely on the deeper soil for its supplies of these essentials

Still another part of the root system is to be described but just how important it became was not ascertained The squash plant takes root at most of the nodes of the prostrate stems At this time these roots were just beginning to develop They were found to penetrate 4 to 8 inches deep and then turn and run laterally, often again approaching the soil surface The shaded and protected vine-covered soil dries slowly and long, thread-like, minutely branched laterals were found just beneath the soil surface These were already often 2 feet long (Fig 89)

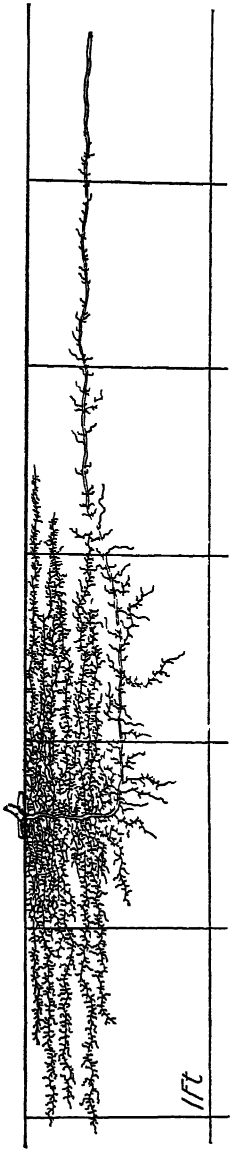


FIG 89 —A typical root originating from the node of a squash vine It is only partially developed

Summary.—The rooting habit of the Hubbard squash is very similar in general plan to that of the watermelon and other

cucurbits The deeper portion of the taproot system is better developed, however, and the shallower part almost as extensive as the coarse, widely spreading vines Plants with a spread of tops of only a foot are rooted 2 5 feet deep and are supplied with numerous, much branched, horizontal laterals 16 to 30 inches in length Thus an efficient absorbing system is developed early Within a period of 2 weeks and when blossoming has just begun, the vines have grown to a length of 6 5 feet The taproots have increased only a foot in length but the horizontal laterals 2 5 feet, thus spreading somewhat less widely than the vines Branching throughout is much more profuse

Maturing plants have a wonderfully intricate and extensive root system which still develops at the rate of approximately 2 5 inches per day A plant with stems 18 and 21 feet long has a taproot which is extensively branched (but with short laterals only, below 2 feet) and reaches the 6-foot level Branches spread rather widely in the second foot but are relatively of less importance than the really wonderful root development in the surface foot of soil A radial spread of 13 to 19 feet is attained Five to seven main roots, with numerous branches 2 to 8 feet long and all again rebranched, form the groundwork which supports a remarkably branched root network that completely ramifies the surface foot of soil Nodal roots, already 4 to 5 feet long and also superficial but extremely well rebranched, increase the absorbing area Thus nearly 1,000 cubic feet of soil give of its supplies of water and nutrients to the support of a single plant

Other Investigations on Squash.—Descriptions and measurements made on a squash plant grown in Massachusetts are of interest since they have been widely quoted and much disputed

> But our squash vine affords the most astonishing demonstration of all that has been said about root development Growing under the most favorable circumstances, the roots attained a number and an aggregate length almost incredible The primary root from the seed, after penetrating the earth about 4 inches, terminated abruptly and threw out adventitious branches in all directions In order to obtain an accurate knowledge of their development, the entire bed occupied by them was saturated with water, and, after 15 hours, numerous holes were bored through the plank bottom, and the earth thus washed away After many hours of most patient labor, the entire system of roots was cleaned and spread out upon the floor of a large room, where they were carefully measured The main branches extended from 12 to 15 feet, and their

total length, including branches, was more than 2,000 feet At every node, or joint, of the vine, was also produced a root One of these nodal roots was washed out and found to be 4 feet long, and to have 480 branches, averaging, with their branchlets, a length of 30 inches, making a total of more than 1,200 feet As there were 70 nodal roots, there must have been more than 15 miles in length on the entire vine There were certainly more than 80,000 feet, and of these, 50,000 feet must have been produced at the rate of 1,000 feet or more per day [26]

The vine grew at a maximum rate of 9 inches per day The total extent of the main vine was 52 feet the lateral branches being removed when 2 to 3 feet long It had 100 leaves The largest leaves were nearly circular and slightly lobed Their diameter was 2 5 feet and the area about 700 square inches [26]

This remarkable root development has been quoted widely in many of the older standard textbooks of botany and plant physiology but later its authenticity was questioned [52] This led to a similar experiment in England with a gourd plant (*Cucumis sativus*) The gourd was grown in a frame 10 by 6 feet in dimensions under the most favorable conditions The roots were examined when the plant was fully grown and had borne 14 fruits The vine with its branches measured 32 feet long and bore 140 leaves The roots were recovered by so carefully washing away the soil that none were lost Careful measurements of both the main root system and the nodal roots gave a total length of 281 feet [52] The small size of the gourd root as compared with that reported for the squash has led some facetious reviewer to remark that the "figure [for the squash] is exaggerated and applies perhaps to Jonah's gourd but not to any other cucurbit"[39]

A careful comparison, however, as regards number and length of main roots with that of the squash plant already described leads one to more nearly accept the Massachusetts findings It is unfortunate that the work was not accurately checked At least it has served a purpose in calling attention to the remarkable extent to which the root systems of cucurbits may develop Of course, length in itself is not of such great significance as absorbing area Many of the larger and older roots rapidly lose the power of absorption and serve only for conduction It may be recalled that root decortication, in the field experiment where the rate of growth and branching was determined, occurred within a week after the new root growth.

Mature squash plants were examined at Geneva, N. Y., where they had grown in a fertile clay loam soil underlaid at a depth of 6 to 10 inches with a tenacious subsoil of gravelly clay.

The roots of this vegetable were examined with considerable interest, because it has been often stated that they extend as far as the runners. Observations showed that this view is based upon fact, indeed, in the bush varieties, the roots extended much further than the stems. In a plant of the Yellow Scallop Bush squash, examined Sept. 8, a root was traced horizontally a distance of 8.5 feet without reaching the end, while the longest runners extended but about 4 feet. This long root grew almost its whole length within 3 inches of the surface. In a plant of the Hubbard squash, of which the roots were washed out Sept. 11, one of them was traced horizontally a distance of 10 feet from the base, and at this point it was $\frac{1}{8}$ inch in diameter, or about a third of its thickness at the start. It might doubtless have been followed much further, but was accidentally broken at this point and the remainder could not be distinguished among many other roots. This long root grew at a depth of 2 to 5 inches below the surface. It frequently changed its course, but pursued in general a rather straight line. It put out branches throughout its length, some of which were $\frac{1}{8}$ inch in diameter. The number of branches in the 10 feet was 385 or on the average 38.5 per foot.[44]

At Saratov, Russia, it was found that the chief mass of the roots of squash occurs in a soil layer not more than 12 to 16 inches deep. The main root had a diameter of 28 millimeters before it began branching at a depth of 2 inches. Beyond 2 inches it tapered gradually to 1 millimeter in thickness at a depth of 39 inches. The soil at this depth was very hard, the root was broken and not traced farther. Below a depth of 16 inches there was very little branching. The largest and longest laterals were found at a depth of approximately 2 to 5 inches in the mellow surface soil layer. The strong horizontal roots spread to distances equal to that of the vines which were 11.5 to 20.3 feet long. The ends of the roots were less than 1 millimeter thick. Some laterals of the second and third order reached a length of nearly 16 feet. With their profuse branches they formed a dense network in the surface soil. The root system was found to be less extensive than that of the watermelon and citron but exceeded that of the muskmelon and cucumber.[76] Other investigations confirmed this study. In the black soil of Russia a great development of horizontal roots occurred in the

plowed horizon, comparatively few roots of the second order penetrated vertically to a depth of about 40 inches.[76a]

These studies all agree in confirming the extensive and superficial rooting habits of the squash and the lesser development of the more deeply penetrating portions.

Root Development in Relation to Cultural Practice.—Both the root and aboveground habits of squash are so similar to the cucurbits already described that it is not surprising that soil preparation, methods of planting, fertilizing, cultivation, etc. are very similar to those already discussed. The chief difference is that the squash is a somewhat hardier plant, does not require so long a growing season, and is not so exacting in its requirements.

In applying barnyard or other coarse manures to the soil, especially where relatively shallow-rooted crops like the cucurbits are grown, it should be the prime object to mix the manure with the soil as thoroughly as possible. If it is turned under in thick layers, without being disintegrated and mixed with the soil to a considerable extent, the layer of manure will prevent the capillary moisture from reaching the upper layer of soil and thus cause the plants to suffer for water very soon during drought. Under such conditions roots have been repeatedly observed to make a vigorous growth in the enriched layer and branch profusely. But when this poorly compacted layer becomes dry the absorbing rootlets die and the main roots merely serve as conductors between the rootlets still functioning in the moist layers below and the parts aboveground. Hence, well-decomposed stable manure is best for the garden, especially when manure is used in large quantities. It is easily mixed with the soil which becomes compacted about it. Thus not only the main roots of the plants but those arising adventitiously from the nodes find a congenial substratum for growth.

Roots of Cucurbits in Relation to Disease.—The development of nodal roots in squash and pumpkin is connected in a measure with recovery from the injuries of certain insect enemies. The squash vine borer in the larval stage of development tunnels into the stem at or near the soil surface. Usually decay sets in, water conduction is interrupted, and the vine begins to wilt. Covering the stems with soil so as to encourage the development of nodal root growth is a common control measure. Although preferring squash and pumpkins, the borer attacks all species of cucurbits, often causing great destruction.

Examples of other disease-producing organisms attacking or gaining entrance through the roots of cucurbits are as follows Watermelon wilt is caused by species of *Fusarium*, fungi which live in the soil and through the roots gain entrance to the water-conducting tissue of the stem When, due to the growth of the fungus, the water supply becomes insufficient the vines suddenly wilt and die Root knot, due to a nematode, causes the roots of watermelons to become greatly enlarged, the vines to lack vigor, and the melons to remain small The striped cucumber beetle tunnels in the main roots or stems of various cucurbits below ground Blossom-end rot is probably a physiological trouble of watermelon brought on by rapid changes in soil moisture just as the young fruits are starting to grow [116]

As pointed out elsewhere, the relation of root development to disease resistance of crops is important and requires intensive study Recent experiments have demonstrated a close relationship between root growth and disease resistance [59] A thorough knowledge of the development of the root habits of cultivated crops is needed in combating plant disease produced by soil-borne parasites or resulting from physiological-environmental relations of the root systems

CHAPTER XXXIII

PUMPKIN

The pumpkin (*Cucurbita pepo*) is a species of the gourd family widely grown as a cultivated annual Like the squash the most common varieties have long-running, prostrate vines, although the variety *condensa* or "bush-pumpkins" are neither running nor tendril bearing and the plants are more compact [7] The pumpkin is grown in practically all portions of the United States but it is of much less commercial importance than the squash In many parts of the United States pumpkins are frequently grown as a companion crop to corn

The Small Sugar variety was planted June 2, in hills 8 feet apart, and at the rate of three plants per hill The first examination was made three weeks later, June 24

Early Growth —The plants were scarcely 6 inches high but had a spread of 1 foot The cotyledons were dead and dry but each plant had about three leaves, ranging from 2 to 3 inches in length and diameter, and a leaf surface of about 25 square inches The stems at the soil surface were 5 to 6 millimeters in diameter but the taproot scarcely exceeded 2 millimeters

The taproot tapered rapidly into a thread-like organ About half of those examined pursued a rather devious course departing 2 to 6 inches from the vertical but all finally reached depths of 18 to 22 inches The characteristic branching habit is shown in Fig 90 Beginning scarcely 1 inch below the soil surface, lateral roots arose at the rate of 7 or 8 per inch to a depth of nearly 9 inches Although many of these were short (6 inches or less), others pursued their horizontal or obliquely outward and downward course extending laterally 12 to 15 inches A few extended outward and upward to within 2 inches of the soil surface A maximum spread of 21 inches was found All of these roots were branched at the rate usually of 6 to 12 rootlets per inch except the 2 to 3 inches of rapidly growing root ends The branches varied from 0 2 to 1 inch in length No tertiary rootlets were found Below 9 inches the laterals were fewer, short, and

unbranched Thus most of the absorbing area at this time was distributed in the 6 to 9 inches of surface soil

Midsummer Growth—The second examination, July 24, showed marked growth both aboveground and underground The main vines were over 7 feet long The plant described had one large branch 5 feet long, originating near the base of the main stem, a second 16 inches distant was 30 inches in length, and a third 2 inches beyond, 32 inches long There were also two short branches The smaller branches had 10 to 13 leaves each,

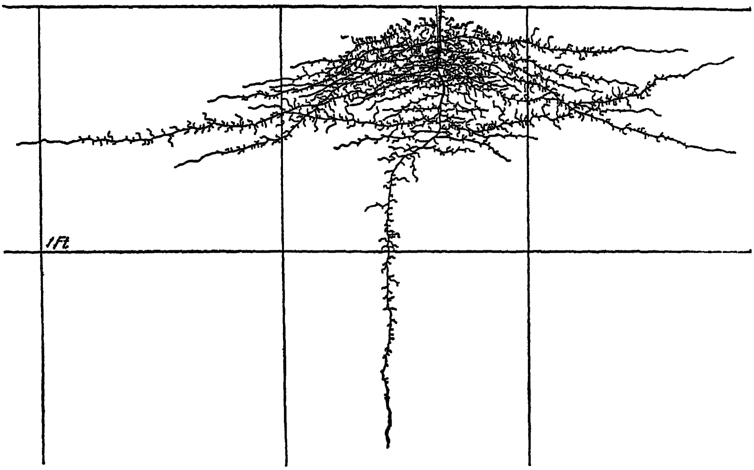


Fig 90—Small Sugar pumpkin 3 weeks old

the larger ones 24, and the main stem 34 Thus a total of nearly 100 large leaves and 75 square feet of leaf surface were exposed to the hot, dry air of midsummer The main vines were nearly 1 inch in diameter at their origin Numerous large flowers further increased the transpiring area A few small fruits were beginning to appear

The root system had made a marked growth The taproots were frequently over 0 5 inch in diameter but tapered rapidly to only 8 millimeters at the 6-inch level In the deeper soil they were only 1 to 2 millimeters thick but the turgid, glistening white root ends again increased to a diameter of 4 millimeters Depths of 4 feet were attained Many of the taproots pursued a rather tortuous course For example, at a depth of 1 foot they were

sometimes 9 inches laterally from the base of the plant and throughout their course they were often much kinked and curved

Most of the large laterals originated at depths of 2 to 10 inches These strong roots were 3 to 6 millimeters in diameter On plants of normal size frequently 10 main laterals arose from this portion of the taproot These, in general, ran horizontally in the surface foot of soil and extended outward from 3 to 8 feet For example, one large branch, originating at the 6-inch level, extended over 7 feet and at no time did it reach a depth greater than 8 inches Thus the roots had spread as widely as the vines Other roots ran laterally only 2 to 3 feet and then turning obliquely or quite horizontally downward often reached depths of 2 to nearly 3 feet These branches sometimes forked rather dichotomously, frequently one of the branches turning downward and the other continuing its horizontal course

All of the larger roots gave rise to long, vertically descending laterals which ramified the second and third foot of soil As many as 12 of these long branches arose from a single root 6 feet in length which pursued its horizontal course between the 4- and 8-inch soil levels These were clothed with an abundance of rootlets of the third order, in fact, so profusely that they formed dense networks at least to 6 inches on all sides of the parent root Other branches on the main laterals arose at the rate of 5 to 10 per inch They ranged from 0 5 to 2 inches in length but, frequently, branches 8 inches in length occurred The longer branches were profusely rebranched, thus greatly increasing their absorbing area

From the first 10 inches of the taproot, moreover, there arose frequently in small groups, short laterals seldom exceeding 4 inches in length, at the rate of three to four per inch In fact the surface 12 inches of soil were so thoroughly occupied and absorption had been so great that they were very dry A few of the root ends had dried out and died But at greater depths moisture was abundant

Below the 10-inch level the roots were relatively short, few exceeded 2 feet in length and the greater number were 8 inches or less Their course was variable Some ran horizontally, others almost vertically downward, still others ran outward and downward The longer ones were so thoroughly rebranched that they formed glistening white, cobwebby mats in the dark-colored, moist soil Branching from the taproot was somewhat

irregular but at the average rate of 5 per inch. Only the longest branches were furnished with rootlets of the third order and those of the second order below 3 feet were rare.

Thus the root system, as in the case of the squash, was differentiating into two parts, one thoroughly ramifying the surface soil, the other, less extensive one, occupying the deeper soil below the hill.

Maturing Plants.—A final examination was made Aug. 24. The plant examined was selected because of its average size and typical appearance. The main stem was 16 feet long. From near its base there arose two long branches, one 13 feet in length with a branch 10 feet long and another 14 feet in length with a single 4-foot branch. In addition, the main vine had three smaller branches 5 to 6 feet in length. The numerous large leaves presented an enormously extensive transpiring area. Many blossoms occurred and eight small fruits about 3 inches in diameter. In addition there were four larger ones 4 to 8 inches in diameter. As in the case of the squash, the root system was composed of two rather distinct parts.

The taproot system, or more strictly speaking its deeper portion, had reached a maximum depth of approximately 6 feet. Although ample rains had moistened the surface soil, the deeper soil was now quite dry and very hard. Depth of penetration (now 6 feet) had been increased about 2 feet over that of the previous examination. In general the branches were slightly more numerous, somewhat longer, and better rebranched. The newer portion of the root was only poorly furnished with laterals. But some of the roots were withered and dry. It seemed that most of the energy of the plant had been used in developing the more superficial portion of the root system.

The extent of the surface root system had been greatly increased. Perhaps a description of a typical lateral will make clear the great extent and complexity of branching. A branch ¼ inch in diameter arose 4 inches below the soil surface. It ran outward 8 inches and branched somewhat dichotomously. Twenty inches from this fork one of the branches gave rise to a small root, only 1 millimeter in diameter, which ran 3 feet and ended in the surface soil. Eight inches farther a similar root arose. It extended vertically downward to a depth of 28 inches where the tip was dead. Eighteen inches farther on the branch a group of six laterals, 0.5 to 1.5 millimeters in diameter,

originated Three of these ran horizontally 22, 31, and 37 inches, respectively, occupying new territory in the shallow soil Two descended almost vertically downward in parallel courses only about 8 inches apart to depths of 24 and 38 inches, respectively The sixth ran obliquely outward and downward ending in a spangle of rootlets which had grown after the main branch had been destroyed The main root, now at a depth of 1 inch, turned abruptly downward 1 inch, ran onward another inch, and then turned quite as abruptly back to its old level Fourteen inches further, a large branch, equal to the main root in diameter, arose This was followed 2 5 feet where it ended in the fifth inch of soil The main root ended 12 feet from its place of origin It was over 14 feet long, however, since it had not pursued a straight course but had curved and turned considerably The other main branch was, in general, not unlike the one described

Only the first foot of the root described was poorly furnished with small laterals These were thread-like and only 3 to 4 inches long Otherwise throughout its course it was branched at the rate of four to eight per inch In addition to the larger branches already described, many of the smaller ones, sometimes three per foot, were 1 millimeter in diameter and 2 to 4 feet long The last 3 feet of the root was 2 millimeters thick, quite white in contrast with the yellowish color of the older parts, and furnished with rootlets 0 2 to 2 5 inches long These were rebranched at the same rate, *i e*, four to eight per inch, as the main root Many of the hairlike branches of the surface root were 3 to 4 inches long and rebranched to the second order Sometimes 15 branches per inch occurred They ran in all directions, frequently upward to near the soil surface The last 6 to 8 inches of main root ends were glistening white, unbranched, and growing rapidly

This is a brief description of one-half of one of the laterals Usually 6 to 10 such roots occurred, running in all directions from the base of the plant Some were smaller (3 millimeters) and shorter, 5 to 8 5 feet A few were longer and even more complex A maximum spread of 17 5 feet was attained by one of the longest roots

The great surface spread of these still rapidly growing roots should be visualized together with the dense network of roots they formed in the surface soil In fact, the root system was

much more branched than that of the squash Attention should also be given to the deeper soil volume occupied by the vertically descending branches

These branches arose in considerable abundance, even at distances of 6 feet from the base of the plant and sometimes were only 3 inches apart Extending to depths of 24 to 38 inches and profusely branched and rebranched throughout, they added greatly to the volume of soil occupied Many root ends, however, had decayed in the dry, hard soil below 3 feet

Some of the larger branches, usually about 6 to 8, originating from the taproot at depths of 5 to 10 inches (rarely deeper) ran outward only 6 to 12 inches and then turned rather obliquely or nearly vertically downward In some cases their course was obliquely downward from the beginning These gave rise to branches both large and small but none showed the horizontal tendency of growth so characteristic in the surface soil They usually penetrated deeply, anywhere from 30 to 45 inches In the hardest soil layer, just above 18 inches, they were poorly branched, usually with 6 to 10 mostly simple branches per inch These were not over 1 to 2 inches long But below this level they were more thrifty and 6 to 8 abundantly rebranched laterals per inch of main root were usual These were rebranched with 8 to 10 sublaterals per inch, some of which were 1 inch long Sometimes 15 branches per inch were found It was evident that conditions for root growth in the deeper soil had been more favorable at an earlier period for now most of the roots below the 3-foot level were in an unhealthy condition

The nodal roots were similar to those of squash Usually the main root reached depths of 3 to 10 inches and then turned and ran horizontally 1 to 2 feet They were densely rebranched Often there were two or three roots originating at one node Roots occurred at most of the nodes but not in such large numbers as were found on the squash

Summary —The Small Sugar pumpkin has a rooting habit somewhat similar to that of the Hubbard squash Three-weeks-old plants have taproots which penetrate downward at the rate of 1 inch per day Major branches occur only in the first 8 inches of soil The longest extends horizontally nearly 2 feet By midsummer the strongly branched vines are over 7 feet long and have 75 square feet of leaf surface The rather crooked taproot has doubled in length Below the surface foot the root

network does not exceed 8 to 24 inches in lateral extent. But in the foot of surface soil the strong laterals, usually about 10 in number, spread outward 3 to 8 feet. Those of lesser spread often turn downward into the second and third foot and all give rise to vertically descending laterals, frequently in great abundance. Both main roots and their branches are so thoroughly furnished with rootlets that not only the surface soil but, to a lesser extent, the second and third foot as well are also fully occupied.

Maturing plants, with vines 16 feet in length, have taproots extending to the 6-foot level. The portion of the root system originating from the taproot below 12 inches makes relatively a small growth when compared with that in the shallower soil. The major surface laterals (usually 6 to 10 in number) are often $\frac{1}{4}$ inch thick and extend outward in rather devious courses 5 to 17.5 feet. Branched throughout their course at the rate of four to eight laterals per inch, many of which are 2 to 4 feet long and all complexly and minutely rebranched, they form a wonderfully efficient root complex. It is even more profuse than that of the squash and like it still grows rapidly. The obliquely penetrating roots extend into the fourth foot of soil. These and the very numerous vertical branches are features not found or at least not prominent in the squash. Descending into the second and third foot in great numbers and often at a distance of 6 feet from the base of the plant, laterals penetrating vertically downward thoroughly ramify the deeper soil. Nodal root development is similar to that of the squash.

The root habits and cultural requirements and practices are so similar to those of other cucurbits that they need not be further discussed.

CHAPTER XXXIV

LETTUCE

The common lettuce of the garden (*Lactuca sativa crispa*) is a tall, leafy, annual herb with a milky juice At first the stem is very short and the foliage densely clustered near the ground, but later in the season a flower stalk, 2 to 4 feet high, appears Lettuce is grown in practically all home gardens, even in cities, and is one of the most important of the salad crops It may be grown under a wide range of conditions In the North it is usually planted in early spring or in the fall, since it makes its best growth during a fairly cool season There are more than 100 distinct varieties [162]

Seed of the Early Prize Head lettuce, one of the curled- or loose-leaf varieties, was planted Apr 10 The rows were 12 inches distant and the plants were thinned so that they were 9 inches apart in the row

Early Growth.—Root development in lettuce takes place rapidly When conditions for growth are very favorable, lateral branches begin to appear on the first 1 to 1 5 inches of taproot only 6 days after the seed is planted and when the cotyledons alone have unfolded

On May 18, at the first field examination, the plants were 2 5 inches tall, had five fully or nearly fully grown leaves, and a top diameter of 6 inches An area of 72 square inches of transpiring surface was found

The pronounced taproots were about 5 millimeters in thickness near the soil surface but gradually tapered to 1 millimeter in diameter They pursued a course almost vertically downward, with only slight deviations, reaching depths of 20 to 28 inches The last 6 to 8 inches were slightly thickened and entirely unbranched (Fig 91) Branches arose in two rows on opposite sides of the taproot The most profuse branching occurred in the surface foot of soil where 20 to 24 roots originated from a single inch On an average, 16 roots arose from the second inch and 7 to 14 per inch at greater depths to the 6-inch soil level

On the deeper root, branches were much fewer, short, and unbranched. Although many of the roots in the surface 6 inches ended within 0.2 inch of the taproot, others extended horizontally 4 to 8 inches and a few had a length of 15 to 17 inches. The older ones near the surface were branched to the third order, the ultimate branchlets sometimes reaching a length of 0.5 inch. Below 4 inches the laterals were unbranched. The superficial

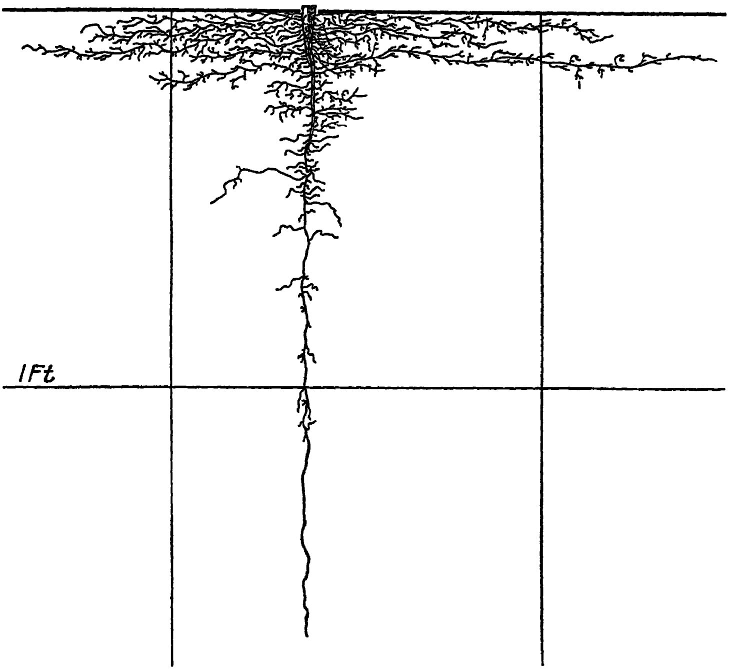


FIG. 91.—Early Prize Head Lettuce 38 days old. Some of the roots lie very near the soil surface.

position of the lateral roots shows clearly the destructive effects that would result even from shallow intertillage.

Effect of Soil Structure on Root Development.—Lettuce was grown in a well-aerated soil with an optimum moisture content, placed in large rectangular containers. In one container the soil was only slightly compacted, in the other it was very compact (p. 39). A dozen lettuce plants were grown in each container. Three weeks later (Apr. 30) the side was cut from each container and the root system examined. The weather had been clear and the plants had grown rapidly. At this time each of them

had four leaves Plants in the compact soil were slightly the larger Depths of 17 to 21 inches were attained by the roots in the loose soil, a maximum depth of only 6 inches was found in the dense soil (Fig 92) In both containers the laterals were about the same length (maximum, 4 inches) just beneath the thin, sand

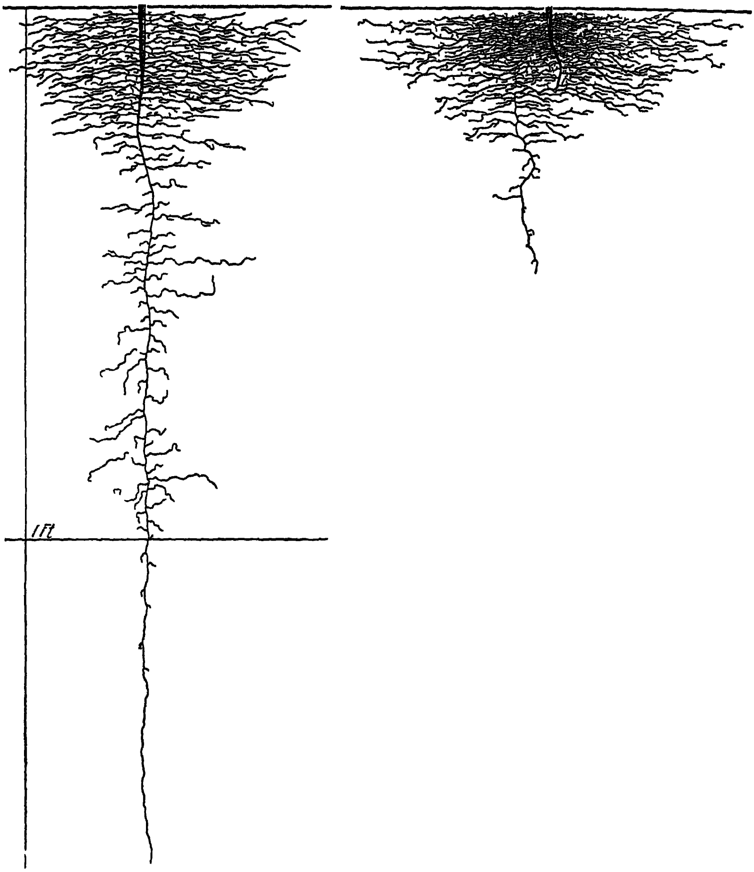


FIG 92 —Lettuce seedlings 3 weeks old The one on the right was grown in compact soil and that on the left in loose soil Both drawings are to the same scale

mulch In the loose soil the taproots pursued an almost vertically downward course and were branched less extensively near the surface but continuously deeper The taproots in the dense soil were branched more profusely in the surface 4 inches

but at greater depths extremely few branches occurred. The main laterals were not only about 25 per cent more numerous, but slightly thicker and more profusely branched. The taproots turned abruptly, apparently having great difficulty in penetrating the compact soil.

Other investigations have shown that the roots of lettuce, like those of most plants, are very susceptible to modification by environment.[89]

Half-grown Plants.—At the time of the second examination, 3 weeks later, June 11, the plants were 8 inches tall. The clusters of 22 to 30 leaves per plant gave the top a total spread of 10 inches. The larger leaves were 5 to 6 inches in length and the width of the leaf was scarcely less. Thus a single plant presented a transpiring area of over 6 square feet. To adequately supply this broad expanse of transpiring tissue with water required a very extensive root system.

The taproot had reached a diameter of ½ inch near the soil surface. But it tapered gradually to about 1 millimeter below 8 inches, a diameter maintained almost throughout its course. It deviated from a vertical path, especially in the more compact soil below 2.5 feet, zigzagging and curving laterally through distances of 1 inch or less. Depths of 40 to 45 inches were attained. The last 3 to 5 inches of the taproot and its major branches were free from laterals. The glistening white or cream-colored roots were easily followed; if broken they exuded drops of the characteristic white latex.

Owing to drought, many of the most superficial roots had died (*cf.* Figs. 91 and 93). No branches occurred on the first ½ inch of taproot but small ones were found on the second. These were nearly ½ millimeter thick and extended laterally only 2 to 4 inches. They were poorly rebranched. But the next 3 inches of taproot gave rise to 57 branches of small diameter (1 millimeter or less) and 9 of larger size (1.2 to 2 millimeters thick). Moreover, 18 small and 4 large branches arose from the next 4 inches of taproot. Figure 93 shows the general outward or outward and downward course of these roots. Although many of the finer ones were only 0.5 to 4 inches in length, others spread 12 inches from the taproot before ending or turning downward. The longest ran almost 30 inches before turning and pursuing a vertically downward course. Many of the larger branches reached the general working level of 24 inches

Branching was profuse For example, one of the larger laterals, originating at a depth of 6 inches, had a total of 102 branches scattered rather regularly over the 20 inches of its horizontal course These were mostly 0 5 to 1 inch in length, occasionally 2 to 5 inches long, and most had a few secondary branches Branches were scarcely less abundant, although somewhat

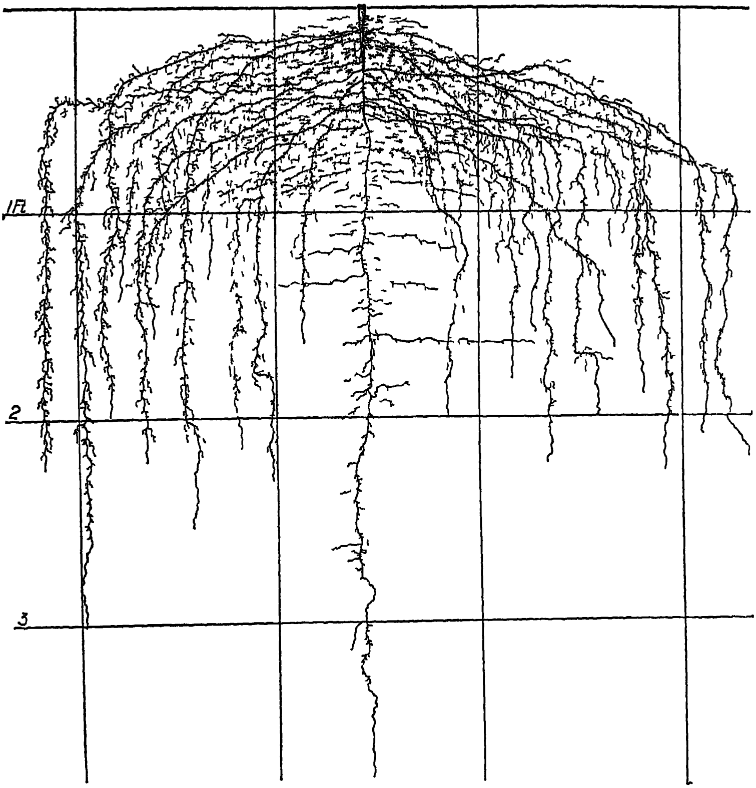


FIG 93—Root system of half-grown lettuce The plant was 2 months old, 8 inches tall, and had about 25 large leaves

shorter, on the vertically descending portions, except on the deepest and youngest part which was unbranched

Below 8 to 10 inches the taproots were clothed with relatively short branches (usually 0 2 to 2 inches long) most of which pursued a horizontal course They were poorly rebranched These sublaterals seldom occurred in greater abundance than four to five per inch In the second to fourth foot the roots

followed the crevices of the soil and seldom branched in more than one plane.

Summarizing, the root habit at this stage of development was characterized by a deep taproot rather poorly branched except in the surface 8 inches of soil and a very large number of widely spreading, well-branched laterals which extended to about 1.5 feet on all sides of the plant and then turned downward and filled the surface 2 feet of soil.

Mature Plants.—By July 13 the flower stalks had reached a height of nearly 3 feet and each had 12 to 18 branches. On some of the stalks blossoms had appeared. The base was covered with about two dozen dead leaves but approximately twice this number of green leaves clothed the remaining portion, the column of foliage having a total diameter of 7 to 8 inches. These stem leaves were somewhat smaller than the earlier basal ones, about 4.5 and 5.5 inches in diameter and length, respectively. The total leaf area was 8.4 square feet.

The development of the root system during the intervening period of 4 weeks was remarkable (Fig. 94). The taproots had extended their depths from about 3.5 feet to the 6- to 7.5-foot level. As before, however, relatively few long branches originated below the first 10 inches. The large laterals, which formerly had reached a depth of only about 2 feet, now extended well into the fourth foot of soil. Some occupied the fifth foot also, and a few of the longest reached a depth of over 6 feet. That growth was still occurring was shown by the long, unbranched turgid root ends. The number of branches filling the soil was much greater than formerly and sublaterals were much more abundant. The total spread, however, had not been increased since the preceding examination. Thus a volume of soil, with a surface area of over 9 square feet and a depth of at least 5 feet—nearly 50 cubic feet—was thoroughly ramified by the roots of a single plant.

The taproot was about 1 inch in greatest diameter and maintained a thickness of 2 millimeters even at a depth of 4 feet. Its course, especially in the deeper soil, was quite tortuous. It frequently turned from the vertical for distances of 1 to 2 inches, sometimes pursuing a horizontal direction of growth. Below 10 inches branches occurred at the rate of only three to seven per inch, their distribution being somewhat irregular. Many were short and thread-like, others were thicker and 3 to 12 inches

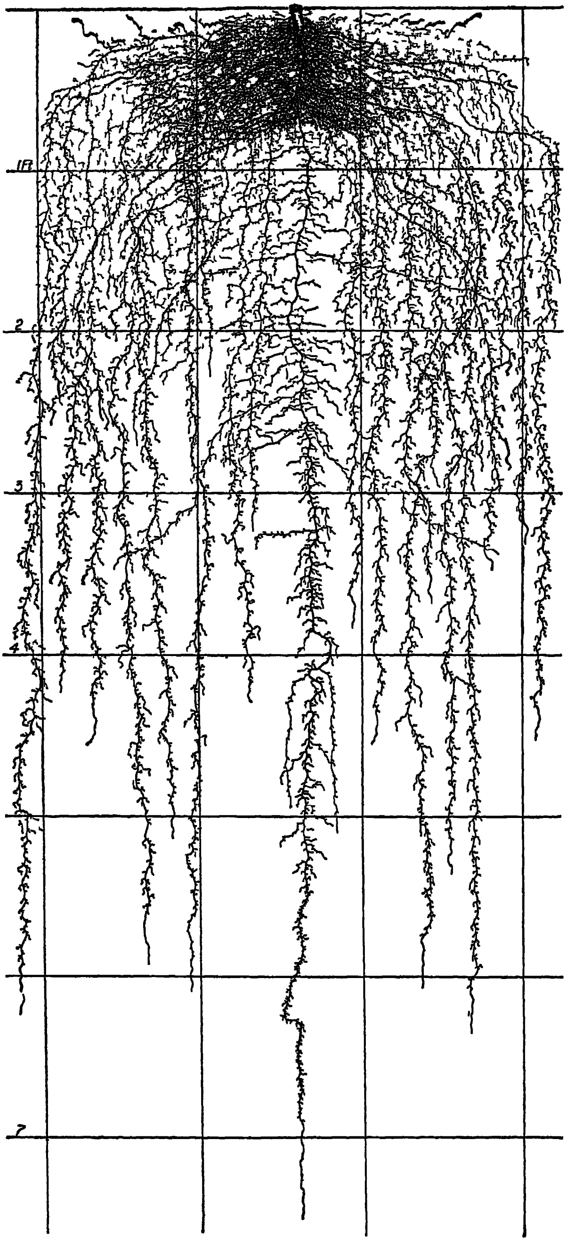


FIG 94 —Mature root system of lettuce The plant was excavated on July 13 and had flower stalks nearly 3 feet tall

long Only the longer ones were much branched Their course was variable, although frequently more or less horizontal

Probably as a result of renewed soil moisture, the surface soil was much better occupied with rootlets than at the June examination From 250 to over 300 roots usually arose from the first 8 inches of the taproot Most of these were only ½ millimeter in diameter although 12 to 20 varied from 1 to 4 millimeters in thickness These large branches ran rather horizontally outward and then downward or obliquely outward and downward before pursuing the somewhat tortuous but generally vertically downward course Nearly all reached depths of 4 to 6 feet All of the older roots were light yellow to tan in color but the younger portions were glistening white Branches from both large and small main laterals were profuse They occurred at the rate of 4 to 15 per inch and varied from 0 2 to 4 inches in length The longer ones were furnished with sublaterals, often rather sparsely, few of which were much rebranched The great network of rootlets will be best appreciated by a close examination of Fig 94 It should also be kept in mind that the root system was not yet fully mature

Summary —Lettuce has a taproot which grows very rapidly, sometimes at the rate of 1 inch per day, especially in loose, moist soil The first laterals are horizontal and very near the soil surface All of the very numerous, large laterals, which become almost equal in diameter and length to the taproot, originate in the surface 10 inches of soil Pursuing an outward or outward and downward course, they extend laterally 6 to 18 inches and then turn downward Before the middle of June the well-branched root system thoroughly occupies the soil to a depth of 2 feet The taproot extends nearly 2 feet deeper But below 1 foot branches from the taproot are scarcely longer than those from the major laterals On maturing plants the roots extend their working level to about 5 feet, and maximum depths of over 6 feet are attained From just beneath the soil surface to deep into the subsoil networks of fibrous rootlets are abundant These are densest in the surface foot of soil

Effect of Cultivation on Root and Shoot Development.—To determine the effect of deep tillage upon the growth of lettuce two adjacent plats were sown, Apr 12, with an uncropped area between them The five rows in each plat were 40 feet long and 12 inches apart and the plants were thinned to 9 inches distant

in the row. One plat was hoed to a depth of 3 inches at five different times between May 21 and July 11 (*cf.* p. 110). The surface of the other plat and that of the uncropped area were scraped to a depth of ½ inch at the times mentioned.

Root examination, June 19, showed that the plants had reached about the same stage of development as shown in Fig. 93. It was found, after careful examination, that many of the large, horizontal, lateral roots in the deeply hoed plat occurred just below the depth to which the soil had been repeatedly disturbed. In the scraped plat the roots were 1 to 1.5 inches nearer the surface.

More than a month later, July 28, it was found that, despite the dry summer, the roots came to within 1 inch of the soil surface. Under the mulch of dead leaves, which extended to a distance of 3 to 5 inches radially from the base of the plant, the surface soil was moist and the roots extended to within 0.5 inch or less of the surface. In the deeply hoed plat few or no roots were found in the surface 3 inches except close to the plant where they had been cut. The roots spread only 20 to 24 inches into the uncropped area which was 10 feet wide so that the middle of this, where soil samples were secured, was free from roots.

After June 7 it was noticed that the lettuce in the deeply hoed plat was distinctly poorer than that in the scraped one. This condition prevailed throughout the summer, several investigators estimating the difference in favor of the shallow-tilled plat to be about 30 per cent. Difference in growth is in accord with the distribution of the root system in the surface soil, deep cultivation causing considerable disturbance to the shallower portion which occupied the richest part of the soil.

An examination of Table 18 shows that the lettuce soon lowered the water content of the surface soil beyond that of the uncropped but scraped area. As the roots penetrated deeper differences in moisture content in the deeper soil became pronounced and these finally extended to a depth of 5 feet. At all depths to 4 feet, the deeply hoed soil had a slightly higher water content than the similarly cropped but scraped plat. This may have been due in part to water conservation by the deep surface mulch—the season being quite dry—and in part to the smaller amount of water absorbed by the less vigorous plants in this plat. This experiment, it should be noticed, extended far beyond the time the lettuce crop was marketable.

TABLE 18.—APPROXIMATE AVAILABLE WATER CONTENT, *i.e.*, AMOUNT ABOVE THE HYGROSCOPIC COEFFICIENT, IN THE SEVERAL PLATS AT LINCOLN, NEB., 1926

Date	Depth, feet	Uncropped, scraped soil	Cropped deeply hoed soil	Cropped, scraped soil	Excess moisture of uncropped over cropped, scraped soil
June 25	0–0.5	10.0	7.2	6.9	3.1
	0.5–1	16.1	10.9	9.4	6.7
	1–2	13.8	14.3	13.6	0.2
	2–3	13.3	13.0	12.3	1.0
July 2	0–0.5	10.3		3.6	6.7
	0.5–1	13.1		9.1	4.0
	1–2	13.4		13.0	0.4
	2–3	13.1		12.0	1.1
July 9	0–0.5	12.0		8.1	3.9
	0.5–1	13.9		7.6	6.3
	1–2	14.4		12.2	2.2
	2–3	13.1		11.5	1.6
	3–4	12.3		11.7	0.6
July 19	0–0.5	6.3		1.3	5.0
	0.5–1	11.0		5.5	5.5
	1–2	14.3		10.1	4.2
	2–3	13.0		7.1	5.9
	3–4	11.8		8.6	3.2
July 28	0–0.5	9.5	10.4	6.3	3.2
	0.5–1	13.6	8.3	6.5	7.1
	1–2	14.8	11.2	9.2	5.6
	2–3	12.9	8.8	6.4	6.5
	3–4	11.5	8.8	7.6	3.9
	4–5	12.1	8.1	8.3	3.8

At Ithaca, N. Y., it was found that lettuce responded more to thorough cultivation than to that cultivation made simply to kill the weeds.

From a study of the root system it appears that those crops which respond least to cultivation, over scraping to keep down weeds, are the ones having the greatest growth of roots. Where there was considerable space between the rows which contained few or no roots, cultivation increased the yield. On the other hand, where the space between the rows was well filled with roots, cultivation did not increase the yield over scraping.[152]

Although much more study is needed, it would seem that the very extensive root system of lettuce together with its early occupancy of the surface soil would lessen the need for cultivation to maintain a soil mulch for water conservation Differences in results may be due to variations in root habit in different varieties as well as to differences in soils and climatic conditions under which the plants are grown

Other Investigations on Lettuce.—Lettuce of the Crisp Small Early Frame variety was washed from the soil at Geneva, N Y, July 9, when the flower stalks were about 6 inches high The taproot extended downward to a depth of more than 25 inches Fibrous roots arose just below the surface of the soil and ran downward at an angle of about 45 degrees They were not traced beyond 1 foot from the taproot The greater part of the fibrous roots lay within 18 inches of the surface and 6 inches on either side of the taproot [43] Lettuce roots are delicate and easily broken It clearly seems that only a small part of the entire root system was uncovered

Certain German investigators conclude that the root system of head lettuce (*Lactuca sativa capitata*) is much like that of the tomato which was found to occupy a cubic volume of soil about 49 inches in each dimension Branches of the second order were most numerous (Table 19) and were thought to do most of the absorbing

TABLE 19 —RATE OF BRANCHING OF HEAD LETTUCE

Age of plant	Number of branches				
	First order	Second order	Third order	Fourth order	Fifth order
25 days	43	62	1		
32 days	59	220	8		
8 weeks	78	790	463	29	
Rather mature (headed)	82	1,442	844	173	2

The branches tend to pursue a rather straight downward course so that the lateral spread is limited to about 12 to 16 inches The depth of the roots of plants 5 weeks old was about 49 inches Sometimes they extended 10 inches deeper [89]

Relation of Root System to Cultural Practice —Although the root system of mature lettuce is very deeply penetrating and profusely branched, that of half-grown plants with marketable tops is not very extensive when compared with those of many vegetable crops Hence, it is important that the soil for lettuce should be moderately deep, well drained, and also retentive of moisture Muck soils are ideal, they are moist, mellow, and easily worked On uplands sandy loams are usually preferred In preparing the soil for lettuce, as for other vegetable crops, it should be plowed deeply The deeper a soil is loosened the more moisture it will hold Deep plowing also promotes better soil aeration, increases nitrification and other bacterial activity, and, as shown by experiment, promotes a more rapid penetration of the roots into the deeper soil

A deep, well-prepared seed bed is essential for good aeration, especially in humid regions It is believed that carbon-dioxide content of garden soils is sometimes so high as to be detrimental to the root development of some common garden species These conclusions are based on experiments with lettuce, peppers, radishes, and beans Where the carbon-dioxide content was high, the roots of lettuce were shorter, spread out horizontally just beneath the surface of the soil and the taproots were abnormally short, crooked, and branching [112, 113]

A good humus content keeps the soil in good physical condition One result is better development of roots Manure is used by nearly all lettuce growers and usually in large quantities Since the crop grows rapidly, the roots must be able to secure an abundance of nutrients easily, hence a soil of good fertility is essential Organic matter is beneficial to the soil and to vegetable crops in many ways It increases the power of the soil to hold water and brings about granulation, which improves both aeration and drainage The presence of organic matter decreases loss by erosion Well-rotted organic matter darkens the color of the soil and thus makes it warm earlier in spring This hastens germination and the early growth of the crop Finally, it furnishes food materials for the plant The thorough distribution of the roots throughout the soil mass shows why the common practice of broadcasting the fertilizer is an excellent one

Thorough preparation of the soil before the crop is sown not only insures a better stand but also makes cultivation both easier and more efficient The frequent shallow intertillage

used in lettuce growing has a double value. It not only reduces root injury to a minimum but also conserves moisture since moist soil is not brought to the surface where it would lose its water directly to the air by evaporation.

Continuing cultivation where there are no weeds and a soil mulch is already formed results in unnecessary labor and expense. In fact, under these conditions cultivation is often positively injurious. The mulch is increased in depth at each cultivation, thus destroying the roots and decreasing the water, making it impossible for the plants to get any moisture or nutrients from the surface 3 or 4 inches.[158]

Thinning of lettuce is more or less injurious to the root system of the plants left for growth. Usually it is considered only in connection with the competition of the plants for light. When it is delayed too long the plants become spindly. "Blocking out" hills with the hoe does not disturb the crop, but the thinning of the remaining plants in a hill to a single individual may be detrimental especially if the process is delayed. Lettuce is easily transplanted and the crop is frequently started from seedlings set in the field. Irrigation is also used to start the crop properly and keep it growing vigorously.[62]

A study of the root systems and of their thorough occupancy of the soil explains why intercropping of cabbage with lettuce, for example, is more likely to be successful where irrigation is practiced than where no provision is made for artificial watering.

BIBLIOGRAPHY

1 Albrecht, W A, and R E Uhland Nitrate accumulation under the straw mulch *Soil Science*, 20 253–267 1925

2 Anonymous The influence of the depth of tillage upon the depth of roots *N Y Agr Exp Sta, Rept* 1888 171–173 1889

3 Anonymous *Storrs Agr Exp Sta, Bull* 3 1889

4 Anonymous Asparagus *Pa Agr Exp Sta, Bull* 147 33-34 1917

5 App, F, and A G Waller Costs, profits, and practices of the can-house tomato industry in New Jersey *N J Agr Exp Sta, Bull* 353 1921

6 Bailey, L H *Cyclopedia of American Horticulture* 7th ed, 4 1712 1910 The Macmillan Company, New York

7 Bailey, L H Manual of cultivated plants 1924 The Macmillan Company, New York

8 Beattie, W R Tomatoes as a truck crop *U S Dept Agr, Farmers' Bull* 1338 1923

9 Beattie, W R Watermelons *U S Dept Agr, Farmers' Bull* 1394 1924

10 Beattie, W R Muskmelons *U S Dept Agr, Farmers' Bull* 1468 1926

11 Beckwith, M H Report of the assistant horticulturist *N Y Agr Exp Sta, Rept* 4 262–263 1886

12 Berkmann, M Investigations on the influence of plant roots on the structure of the soil *Intern Mitt Bodenk*, 3 1 49 1913 (Abstract in *Exp Sta Rec*, 30 120-121 1914)

13 Bishop, W H, and H J Patterson Tomatoes *Md Agr Exp Sta, Bull* 11 1890

14 Boyle, J G, and J B Abbott Tomato investigations *Ind Agr Exp Sta, Bull* 165 1913

15 Brenchley, W E, and K Singh Effect of high root temperature and excessive insolation upon growth *Ann Appl Biol*, 9 197–209 1922

16 Brooks, W P, and F W Morse A fertilizer experiment with asparagus *Mass Agr Exp Sta, Bull* 194 1919

17 Brown, H D Growing tomatoes for the canning factory *Ind Agr Exp Sta, Bull* 288 1924

18 Brown, P E, and J H Stallings Inoculated legumes as nitrogenous fertilizers *Soil Science*, 12 365–407 1921

19 Bunyard, E A The history and development of the strawberry *Jour Roy Hort Soc*, 39 541–552 1914

20 Burns, G P Studies in tolerance of New England forest trees *Vt Agr Exp Sta, Bull* 178 1914

21 CANNON, W A The influence of the temperature of the soil on the relation of roots to oxygen *Science*, n s, 58 331–332 1923

22 CANNON, W A Physiological features of roots, with especial reference to the relation of roots to aeration of the soil *Carnegie Inst Wash*, *Pub* 368 1925

23 CANNON, W A Experimental studies on roots *Carnegie Inst Wash*, *Year Book*, 24 289–298 1925

24 CARSTENS, C C Rhubarb culture *N Y Agr Exp Sta*, *Circ* 38 1915

25 CATES, J S, and H R COX The weed factor in the cultivation of corn *U S Dept Agr*, *Bur Plant Ind*, *Bull* 257 1912

26 CLARK, W S Observations upon the phenomena of plant-life *Mass Bd Agr*, *Rept* 1874, 22 211–213 1875

27 CLEMENTS, F E Aeration and air-content, the role of oxygen in root activity *Carnegie Inst Wash*, *Pub* 315 1921

28 CORBETT, L C Vegetables *W Va Agr Exp Sta*, *Bull* 49 1897

29 CRANEFIELD, F The effect of transplanting on time of maturity *Wis Agr Exp Sta*, *Rept* 16 312–315 1899

30 CRIST, J W, and J E WEAVER Absorption of nutrients from subsoil in relation to crop yield *Bot Gaz*, 77 121–148 1924

31 DE BAUN, R W Sweet potato culture and storage in New Jersey *N J Agr Exp Sta*, *Circ* 114 1919

32 ELLIOTT, G R B Relation between the downward penetration of corn roots and water level in peat soil *Ecology*, 5 175–178 1924

33 FITE, A B Growing early cabbage *N M Agr Exp Sta Bull* 151 1926

34 FRUWIRTH, C Ueber die Ausbildung des Wurzelsystems der Hulsenfruchte *Forshungen auf dem Gebiete der Agrikultur-Physik*, 18 461–479 1895

35 GAIN, E Influence de l'humidité sur le développement des nodosites des Légumineuses *Compt Rend Acad Sci*, 116 1394–1397 1893

36 GARCIA, F Chile culture *N M Agr Exp Sta*, *Bull* 67 1908

37 GARCIA, F Sweet potato culture *N M Agr Exp Sta*, *Bull* 70 1909

38 GARCIA, F New Mexico beans *N M Agr Exp Sta*, *Bull* 105 1917

39 *Gardeners' Chronicle*, 3d ser, 53 347 1913

40 GARDNER, V R, F C BRADFORD, and H D HOOKER The fundamentals of fruit production p 587 McGraw-Hill Book Company, Inc, New York 1922

41 GARNER, W W, W M LUNN, and D E BROWN Effects of crops on the yields of succeeding crops in the rotation, with special reference to tobacco *Jour Agr Res*, 30 1095–1132 1925

42 GOFF, E S Root washings *N Y Agr Exp Sta*, *Rept* 1883, 2 219 1884

43 GOFF, E S Root washings *N Y Agr Exp Sta*, *Rept* 1884, 3 305–315 1885

44 GOFF, E S Observations on root growth *N Y Agr. Exp Sta*, *Rept* 1886, 5 157–165 1887

45 GOFF, E S A study of the roots of certain perennial plants *Wis Agr Exp Sta, Rept* 14 286–298 1897
46 GOFF, E S The resumption of root growth in spring *Wis Agr Exp Sta, Rept* 15 220–228 1898
47 GREAVES, J E, and E G CARTER Influence of moisture on the bacterial activities of the soil *Soil Science,* 10 361–387 1920
48 HAASIS, F W Relations between soil type and root form of western yellow pine seedlings *Ecology,* 2 292–303 1921
49 HALL, F H Culture of asparagus *N Y State Col Agr at Cornell Univ, Ext Bull* 81 1924
50 HARRIS, F S The effect of soil moisture, plant food, and age on the ratio of tops to roots in plants *Jour Am Soc Agron,* 6 65–75 1914
51 HARTWELL, B L, F R PEMBER, and G E MERKLE The influence of crop plants on those which follow, II *R I Agr Exp Sta, Bull* 176 1919
52 HARVEY GIBSON, R J The extent of the root system of Cucumis sativus *Ann Bot,* 26 951–952 1912
53 HASSELBRING, H Behavior of sweet potatoes in the ground *Jour Agr Res,* 12 9–17 1918
54 HELM, C A Corn in Missouri *Mo Agr Exp Sta, Bull* 185 1921
55 HENDRY, G W Bean culture in California *Calif Agr Exp Sta, Bull* 294 1921
56 HOFFER, G N, and R H CARR Accumulation of aluminium and iron compounds in corn plants and its probable relation to root rots *Jour Agr Res,* 23 801–823 1923
57 HOFFER, G N, and J F TROST The accumulation of iron and aluminium compounds in corn plants and its probable relation to root rots, II *Jour Am Soc Agron,* 15 323–331 1923
58 HOLBERT, J R, *et al* Corn root, stalk, and ear rot diseases, and their control thru seed selection and breeding *Ill Agr Exp Sta, Bull* 255 1924
59 HOWARD, A Disease in plants *Agr Jour India,* 16 626–637 1921
60 HOWARD, A, Director, Institute of Plant Industry, Indore, Central India Correspondence 1926
61 HOWARD, G L C The role of plant physiology in agriculture *Agr Jour India,* 18 204–218 1923
62 HUBER, H F Lettuce growing in New Jersey *N J Agr Exp Sta, Circ* 155 1924
63 HUBER, H F Spring cauliflower in New Jersey *N J Agr Exp Sta, Bull* 432 1926
64 HULBERT, H W Field pea production in north Idaho *Idaho Agr Exp Sta, Bull* 115 1919
65 HUTCHINS, L M, and B E LIVINGSTON Oxygen-supplying power of the soil as indicated by color changes in alkaline pyrogallol solution *Jour Agr Res,* 25 133–140 1923
66 JARVIS, C D American varieties of beans. *Cornell Univ Agr Exp Sta, Bull* 260 1908.

67 JEAN, F C Unpublished data, Department of Botany, University of Nebraska 1925
68 JEAN, F C, and J E WEAVER Root behavior and crop yield under irrigation *Carnegie Inst Wash, Pub* 357 1924
69 JENSEN, C A Relation of inorganic soil colloids to plowsole in citrus groves in southern California *Jour Agr Res*, 15 505–519 1918
70 JONES, H A Tomatoes for market and canning *Md Agr Exp Sta, Bull* 248 1922
71 JONES, H A, and W W ROBBINS Growing and handling asparagus crowns *Calif Agr Exp Sta, Bull* 381 1924
72 JONES, L R The relation of environment to disease in plants *Am Jour Bot*, 11 601–609 1924
73 JONES, L R, *et al* Fusarium resistant cabbage *Wis Agr Exp Sta, Res Bull* 48 1920
74 JONES, L R, and J C GILMAN The control of cabbage yellows through disease resistance *Wis Agr Exp Sta, Res Bull* 38 1915
75 JONES, L R, and W B TISDALE Effect of soil temperature upon the development of nodules on the roots of certain legumes *Jour Agr Res*, 22 17–31 1921
76 KARTASHOVA, S The root-system of water-melons, melons and cucurbits *Bull Appl Bot and Plant Breed*, 14 79–87 1925
76*a* KAZAKEVITCH, L I Abstract of work done at the sub-station of applied botany, 1924 Saratov 1925
77 KEZER, A, and W G SACKETT Beans in Colorado and their diseases *Colo Agr Exp Sta, Bull* 234 1918
78 KIESSELBACH, T A Transpiration experiments with the corn plant *Neb Agr Exp Sta, Rept* 23 125–129 1910
79 KILTZ, B Root habits of seventeen common Nebraska weeds 1927 Unpublished thesis, Department of Agronomy, University of Nebraska
80 KING, F H Natural distribution of roots in field soils *Wis Agr Exp Sta, Rept*, 1892 112, also 1893 160
81 KOEHLER, B, G H DUNGAN, and J R HOLBERT Factors influencing lodging in corn *Ill Agr Exp Sta, Bull* 266 1925
82 KRASSOVSKY, I Physiological activity of the seminal and nodal roots of crop plants *Soil Science*, 21 307–325 1926
83 KRAUS, C Das Wurzelsystem der Runkelruben und dessen Beziehungen zur Rubenkultur *Forschungen auf dem Gebiete der Agrikultur-Physik*, 11 358–406 1888
84 KRAUS, C Untersuchungen uber die Bewurzelung der Kulturpflanzen in physiologischer und kultureller Beziehung *Forschungen auf dem Gebiete der Agrikultur-Physik*, 15 234–286 1892
85 *Ibid* 17 55–103 1894
86 *Ibid* 18 113–166 1895
87 *Ibid* 19 80–129 1896
88 KRAUS, C Zur Kenntnis der Verbreitung der Wurzeln in Bestanden von Rein- und Mischsaaten *Fuhlings landw Ztg*, 63 337–362, 369–383, 401–412, May-June, 1914

89 KROEMER, K Beobachtungen uber die Wurzelentwicklung der Gemusepflanzen *Landw Jahrb*, 51 731–745 1918

90 LATTA, W C Field experiments with corn *Ind Agr Exp Sta*, *Bull* 39 35 1892

91 LLOYD, J W Fertilizer experiments with muskmelons *Ill Agr Exp Sta*, *Bull* 155 1912

92 LLOYD, J W How to grow muskmelons *Ill Agr Exp Sta*, *Circ* 139 1922

93 LLOYD, J W Onion culture *Ill Agr Exp Sta*, *Circ* 173 1926

94 LLOYD, J W Some tests in the culture of peppers *Ill Agr Exp Sta*, *Bull* 274 1926

95 LLOYD, J W, and I S BROOKS Growing tomatoes for early market *Ill Agr Exp Sta*, *Bull* 144 1910

96 LOHNIS, F, and R HANSEN Nodule bacteria of leguminous plants *Jour Agr Res*, 20 543–557 1921

97 LOOMIS, W E Studies in the transplanting of vegetable plants *Cornell Univ Agr Exp Sta*, *Mem* 87 1925

98 LYON, T L Experiments with corn *Neb Agr Exp Sta*, *Bull* 91 1905

99 MCCUE, C A, and W C PELTON Tomatoes for the canning factory *Del Agr Exp Sta*, *Bull* 101 1913

100 MCGINTY, R A The home vegetable garden *Colo Agr Exp Sta*, *Bull* 276 1922

101 MCGINTY, R A High altitude vegetable growing *Colo Agr Exp Sta*, *Bull* 309 1926

102 MARBUT, C F Soils of the Great Plains *Ann Assoc Am Geog* 13 41–66 1923

103 MAXIMOW, N A, and E LEBEDINCEV Uber den Einfluss von Beleuchtungsverhaltnissen auf die Entwickelung des Wurzelsystems *Ber Deutsch bot Ges*, 41 292–297 1923

104 MILLAR, C E Hill fertilization of corn *Mich Agr Exp Sta*, *Quart Bull* 5 69–73 1922

105 MILLER, E C Comparative study of the root systems and leaf areas of corn and the sorghums *Jour Agr Res*, 6 311–332 1916

106 MILLS, H S, and L J NORTON Growing peas for the canning factory *N Y State Col Agr at Cornell Univ*, *Ext Bull* 95 1924

107 MONTGOMERY, E G The corn crops p 179 1913

108 MORSE, F W A chemical study of the asparagus plant *Mass Agr Exp Sta*, *Bull* 171 1916

109 MOSIER, J G, and A F GUSTAFSON Soil moisture and tillage for corn *Ill Agr Exp Sta*, *Bull* 181 1915

110 MYERS, C E Experiments with cabbage *Pa Agr Exp Sta*, *Bull* 137 1916

111 NEWMAN, C L Sweet potato experiments *Ark Agr Exp Sta*, *Bull* 72 1902

112 NOYES, H A, J F TROST, and L YODER Root variations induced by carbon dioxide gas additions to soil *Bot Gaz*, 66 364–373 1918

113 NOYES, H A, and T H WEGHORST Residual effects of carbon dioxide gas additions to soil on roots of Lactuca sativa *Bot Gaz*, 69 332–336 1920
114 OSKAMP, J Strawberry varieties and cultural hints *Ind Agr Exp Sta*, *Bull* 200 1917
115 PACK, D A Time of year to plant mother beets for seed production *Jour Agr Res*, 30 811–818 1925
116 QUINN, J T Tomato culture in Missouri *Mo Agr Exp Sta*, *Bull* 212 1924
117 RICKS, J R Corn *Miss Agr Exp Sta*, *Bull* 170 1915
118 ROBBINS, W W The botany of crop plants 2d ed P Blakiston's Son and Co, Philadelphia 1924
119 ROGERS, C F, L W DURRELL, and L B DANIELS Three important perennial weeds of Colorado *Colo Agr Exp Sta*, *Bull* 313 1926
120 ROSA, J T Better methods of tomato production *Mo Agr Exp Sta*, *Bull* 194 1922
121 ROSA, J T Tomato production in California *Calif Agr Exp Sta*, *Circ* 263 1923
122 ROSA, J T Sweet potato production in California *Calif Agr Exp Sta*, *Circ* 285 1925
123 ROTMISTROV, V The distribution of the roots of some annual cultivated plants *Zhurnal opuitnoi agronomii*, 8 511–533, 667–705 1907
124 *Ibid* 9 1–24 1908
125 ROTMISTROV, V Root system of cultivated plants of one year's growth Odessa 1909
126 ROTMISTROV, V The nature of drought according to the evidence of the Odessa Experiment Field Odessa 1913
127 RUSSELL, E J Soil conditions and plant growth p 39 Longmans, Green & Co, London 1917
128 RUSSELL, E J Plant nutrition and crop production p 45 University of California Press, Berkeley 1926
129 RUSSELL, E J, and F R PETHERBRIDGE On the growth of plants in partially sterilized soils *Jour Agr Sci*, 5 248–287 1913
130 RUSSELL, J C, E G JONES, and G M BAHRT The temperature and moisture factors in nitrate production *Soil Science*, 19 381–398 1925
131 SAHUT, F De l'influence directe du sujet sur le greffon *Rev Hort* 57 305–309 1885
132 SCHERMERHORN, L G Sweet potato studies in New Jersey *N J Agr Exp Sta*, *Bull* 398 1924
133 SCHULZE, B Studien uber die Bewurzelung unserer Kulturpflanzen *Festschrift* 50, *Jubilaum Agr Chem Versuchs- u Kontrollstat*, Breslau, pp 67–95 1906
134 SCHULZE, B Wurzelatlas Berlin, vol 1, 1911, vol 2, 1914
135 SEWELL, M C Tillage a review of the literature *Jour Am Soc Agron*, 11 269–290 1919.

136 SEWELL, M C Effect of Andropogon sorghum on succeeding crops of Triticum sativum vulgare *Bot Gaz*, 75 1–26 1923
137 SHAW, G W, and M E SHERWIN The production of the lima bean the need and possibility of its improvement *Calif Agr Exp Sta*, *Bull* 224 1911
138 SIDERIS, C P Observations on the development of the root system of Allium cepa L *Am Jour Bot*, 12 255–258 1925
139 SMITH, O Steam sterilization of greenhouse soil and its effect upon the root system of the tomato A thesis Dept Horticulture, Iowa State College 1924
140 SMITH, O Steam sterilization of greenhouse soil and its effect upon the root system of the tomato *Proc Am Soc Hort Sci*, 1925, 22 312–314 1926
141 SMITH, L H, and E H WALWORTH Seminal root development in corn in relation to vigor of early growth and yield of crop *Jour Am Soc Agron*, 18 1113–1120 1926
142 SORAUER, P Manual of plant diseases 3d ed, translated by F Dorrance, 1 841 1920
143 STARNES, H N Sweet potatoes *Ga Exp Sta*, *Bull* 25 1894
144 STEWART, G Field beans *Utah Agr Exp Sta*, *Circ* 37 1919
145 STUCKEY, H P Tomatoes *Ga Exp Sta*, *Bull* 112 1915
146 STUCKEY, H P Watermelons *Ga Exp Sta*, *Bull* 143 1924
147 TALBERT, T J Missouri strawberries *Mo Agr Exp Sta*, *Bull* 242 1926
148 TANSLEY, A G, and T F CHIPP Classification of mature soils according to climatic soil types In "Aims and Methods in the Study of Vegetation," pp 131–135 Published by The British Empire Vegetation Committee and The Crown Agents for the Colonies, 4 Millbank, Westminster, S W, London 1926
149 TEN EYCK, A M A study of the root systems of cultivated plants grown as farm crops *N D Agr Exp Sta*, *Bull* 43 1900
150 THOMPSON, H C Strawberry growing in the south *U S Dept Agr Farmers' Bull* 664 1915
151 THOMPSON, H C Asparagus *U S Dept Agr*, *Farmers' Bull* 829 1917
152 THOMPSON, H C Effects of cultivation on soil moisture and on yields of certain vegetables *Proc Am Soc Hort Sci*, 1920, 17 155–161 1921
153 THOMPSON, H C Vegetable crops p 99 McGraw-Hill Book Company, Inc, New York 1923
154 *Ibid* p 135
155 *Ibid* p 253
156 *Ibid* p 310
157 *Ibid* p 378
158 THOMPSON, H C Experimental studies of the effects of cultivation on certain vegetable crops *Proc Am Soc Hort Sci*, 1924, 21 108–115 1925
159 THOMPSON, H C Results of sweet-corn suckering experiments. *Cornell Univ Agr Exp Sta*, *Bull* 450 1926

159a THOMPSON, H C Experimental studies of cultivation of certain vegetable crops *Cornell Univ Agr Exp Sta, Mem* 107 1927 In press

160 TOUMEY, J W Initial root habit in American trees and its bearing on regeneration Address at the Fourth International Botanical Congress at Cornell University, Ithaca, N Y, Aug 17, 1926 Unpublished

161 TOUMEY, J W, and E J NEETHLING Insolation a factor in the natural regeneration of certain conifers *Yale Univ School Forest, Bull* 11 1924

162 TRACY, W W American varieties of lettuce *U S Bur Plant Ind, Bull* 69 1904

163 TROMMER, M Untersuchungen uber den Einfluss der mèchanischen Bodenbeschaffenheit auf das Wachstum der Wurzeln *Landw Jahrb Bayern,* 10 163–219 1920

164 TUCKER, M, and C VON SEELHORST Der Einfluss der Wassergehalt und der Reichtum des Bodens auf die Ausbildung der Wurzeln und der oberirdischen Organe der Haferpflanze ausuben *Jour Landw,* 46 52–63 1898

165 VOROB'EV, S I On the study of the root systems of cereals and forage plants *Selsk Khoz Liesov,* 251 477 1916

166 WATERS, H J Field experiments with corn *Mo Agr Exp Sta, Bull* 14 19 1891

167 WEAVER, J E The ecological relations of roots *Carnegie Inst Wash, Pub* 286 1919

168 WEAVER, J E Root development in the grassland formation, a correlation of the root systems of native vegetation and crop plants *Carnegie Inst Wash, Pub* 292 1920

169 WEAVER, J E Investigations on the root habits of plants *Am Jour Bot,* 12 502–509 1925

170 WEAVER, J E Relation of soil temperature to disease in plants In "Root Development of Field Crops," pp 26–28 McGraw-Hill Book Company, Inc, New York 1926

171 *Ibid* Correlation between root and shoot development pp 73–75

172 *Ibid* Grass roots in relation to soil structure and productivity pp 204–205

173 *Ibid* Variations in root habit under competition pp 249–252

174 WEAVER, J E, F C JEAN, and J W CRIST Development and activities of roots of crop plants, a study in crop ecology *Carnegie Inst Wash, Pub* 316 1922

175 WERNER, H O Tomatoes for North Dakota *N D Agr Exp Sta, Bull* 111 1915

176 WICKS, W H Tomato culture in Idaho *Idaho Agr Exp Sta, Bull* 76 1913

177 WICKS, W H Strawberry growing in Arkansas *Ark Agr Exp Sta, Bull* 122 1915

178 WICKS, W H Sweet potato culture in Arkansas *Ark Agr Exp Sta, Bull* 124 1915

179 WILLIAMS, C G, and F A WELTON Corn experiments *Ohio Agr Exp Sta, Bull* 282 1915

180 WILSON, J K Physiological studies of Bacillus radicicola of soybean (Soja max Piper) and of factors influencing nodule production *Cornell Univ Agr Exp Sta, Bull* 386 1917

181 WIMER, D C, and M B HARLAND The cultivation of corn, weed control *vs* moisture conservation *Ill Agr Exp Sta, Bull* 259 1925

182 YEAGER, A F Onion growing in North Dakota *N D Agr Exp Sta, Bull* 173 1924

INDEX

(Figures in Boldface Type Indicate Pages on Which Illustrations Occur)

S